JOURNAL

of the

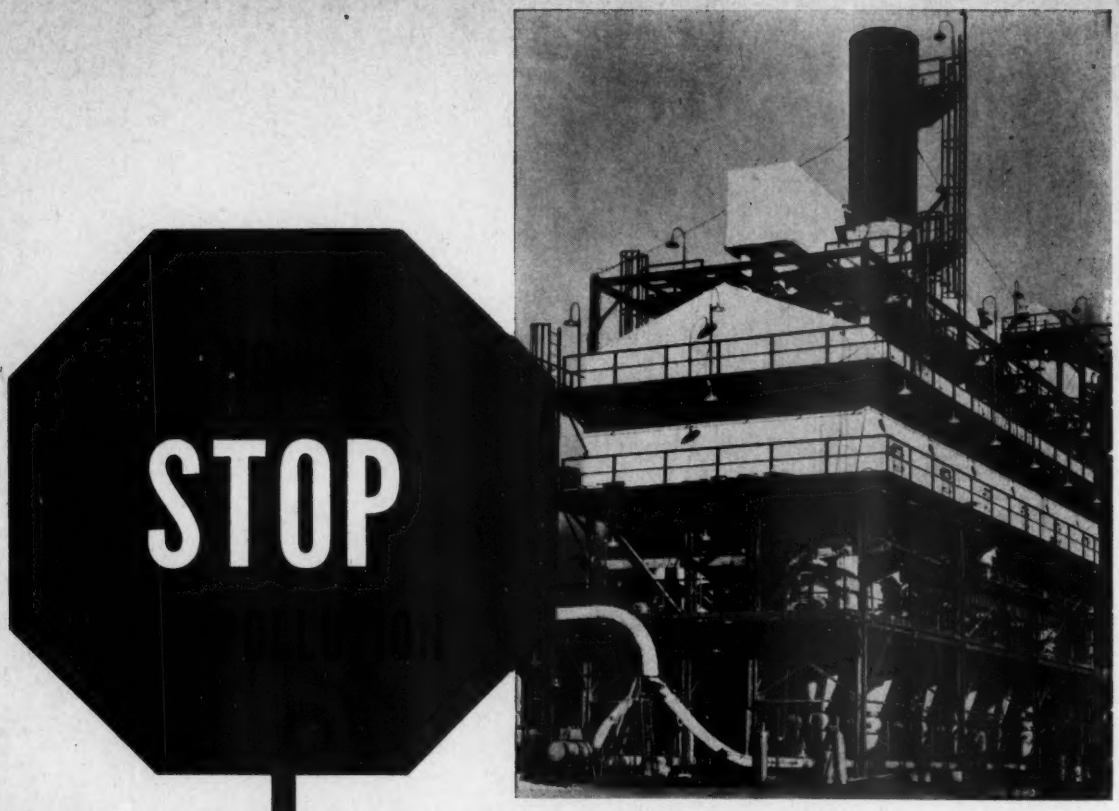
AIR POLLUTION CONTROL ASSOCIATION

Founded 1907

February 1957
Vol. 6, No. 4

A Venturi Throat

(see page 219)



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Behind Koppers successful solutions to every type of industrial air pollution problem lies three-quarters of a century of research and development in this country and abroad. From all this "know-how" come the basic types of gas cleaning units, produced by Koppers, that can solve any gas cleaning problem you may have.

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Koppers New Cyclonic Type Dust Collectors. Produced after intensive study and experience, Koppers Mechanical Dust Collector provides maximum efficiency in mechanical dust removal.

Koppers Aeroturn Dust Collectors. Automatic pressure control and reverse-air-jet action provide high, continuous filtering. Clean air, reclaimed materials. Felt-type filters are more efficient; last longer.

An important message

to the man who thinks his air pollution problem is too difficult—or too expensive—to correct

Too often an air pollution problem exists today for one reason only: The company concerned does not yet know there is now at hand an efficient, effective method of correcting it—often at an actual saving through waste heat recovery.

The method is catalytic oxidation, and the firm that makes this development possible is Oxy-Catalyst, Inc.

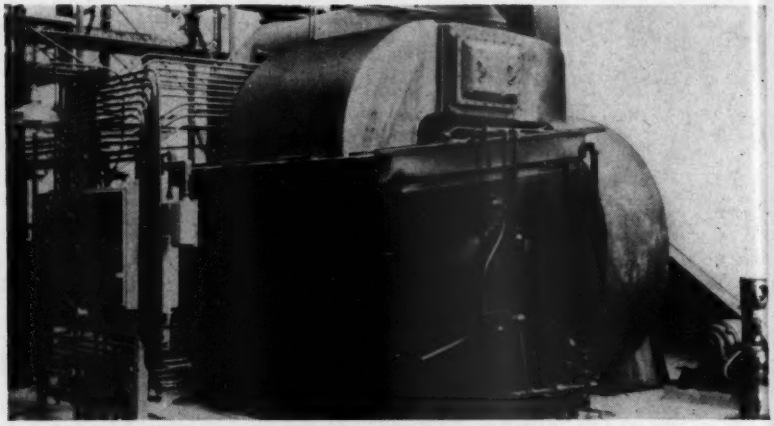
Catalytic oxidation works by "burning" harmful and irritating combustible contaminants in an exhaust stream at temperatures far below their normal ignition points. It provides close to 100% cleanup of foul-smelling fumes and odors. It reduces fire hazards and maintenance problems by eliminating troublesome condensates in oven and furnace exhausts.

Thus Oxy-Catalyst installations can not only control air pollution. They can also be used to release the latent heat energy in waste and process gases. And they can sometimes do both at once.

A More Efficient Catalyst

The key to successful catalytic oxidation is, of course, the catalyst itself. Features which make the Oxycat unique are:

- *The combination of platinum and alumina, chosen from hundreds of elements and compounds as the most active and long lasting catalytic agent*
- *The carrier, a high-grade porcelain selected for its strength, chemical inertness, and resistance to high temperatures*
- *The patented method of applying the catalyst to the carrier*
- *The patented mechanical design of the Oxycat itself*



Oxycat installation on Standard Oil Company of California's phthalic anhydride unit at Richmond, Calif.

The result of this combination of features is a catalytic unit with exceptionally long life at high efficiency. Oxycats are strongly resistant to thermal shock—to contaminating agents and clogging. There's no problem of frequent cleaning or reprocessing. Oxy-Catalyst installations are still functioning at high initial efficiency after over 20,000 hours without maintenance or servicing.

Already in Wide Use

Oxy-Catalyst installations are now working effectively in a wide range of industries—oxidizing combustibles from such processes as asphalt oxidation; phthalic anhydride, polyethylene and ethylene oxide manufacturing; catalytic cracking; and many others.

Oxy-Catalyst installations are carefully engineered to your individual requirements, and our engineers, working with yours, can install Oxycats effectively in any existing plant. So, if air pollution is a problem in your operation—if irritating fumes and odors are costing you neighborhood good will—you should know that Oxy-Catalyst offers a practical, realistic answer to your problem.

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Industrial Division

Wayne, Pa., U.S.A.

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Industrial • Automotive • Consumer Products

Oxy-Catalyst, Inc.
Industrial Division, Wayne 11, Pa.

Please send me complete information on your catalytic oxidation process for air pollution control and waste heat recovery.

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Firm name_____

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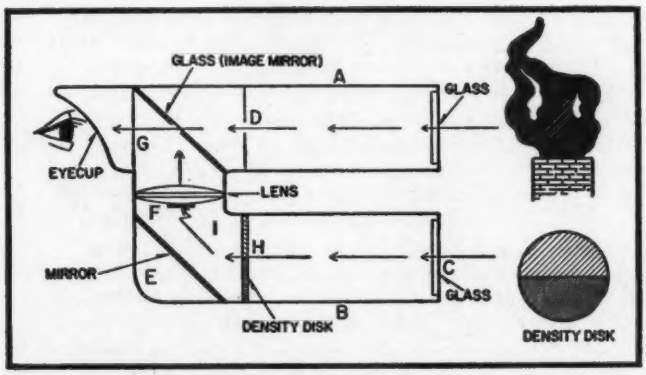
the M-S-A SMOKESCOPE*

- **Precision built, optically accurate instrument designed for estimating the density of smoke in stack effluent.**

Because limitations imposed by smoke control laws are generally based on an established maximum permissible smoke density in stack effluent, a reliable method of estimation is essential to proper compliance. The M-S-A Smokescope was designed to fill this need.

In the Smokescope, a reference standard film disc receives light from the same source as does the smoke. This minimizes background differences because they affect the smoke and reference disc equally. Ambient light plays no part in the observation. A lens, which projects disc image to a focal distance equivalent to that of smoke, permits comparison without changing eye focus.



- ***How it works***—**Smoke picture fills field of vision through apertures C, D, and G. Light from area adjacent to stack is transmitted through reference disc, H, in barrel, B, to surface of mirror, E. Image of reference disc projects through lens, F, to image mirror where it is compared with smoke seen through apertures. Center of reference disc is blocked by opaque disc, I.**

Write for complete details.

***As described in the U.S. Bureau of Mines Report of Investigation, R.I. 5162**

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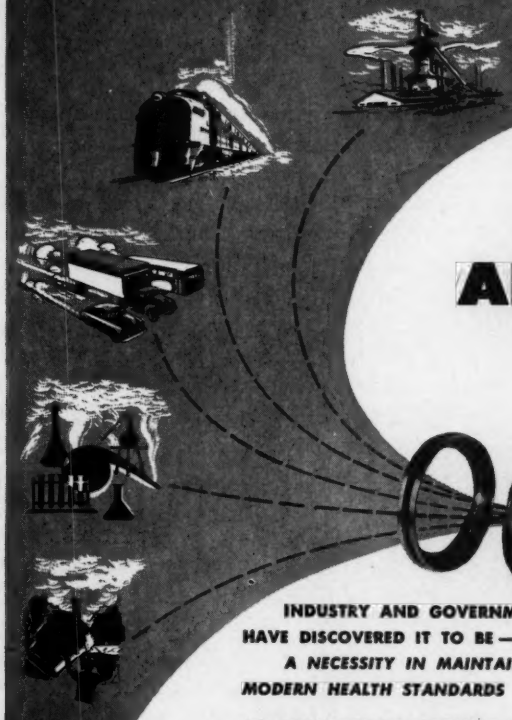
TO COMBAT AIR POLLUTION . . .



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A NECESSITY IN MAINTAINING MODERN HEALTH STANDARDS

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Originally designed in the Atomic Energy Commission, (N. Y. office), the STAPLEX HI-VOLUME AIR SAMPLER's prime purpose is for accurately sampling large volumes of air for particulate matter by means of filter papers. *It accurately samples air containing particles as small as 1/100th of a micron in diameter.*

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FOUNDED 1907

JOURNAL OF THE AIR POLLUTION CONTROL ASSOCIATION

Formerly "Air Repair"

A QUARTERLY JOURNAL DEVOTED TO AIR PURIFICATION

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The Editor welcomes writers interested in air pollution problems and encourages them to use the pages of this journal for the expression of their opinions. But neither he nor the Association assumes responsibility for the validity of the opinions expressed herein.

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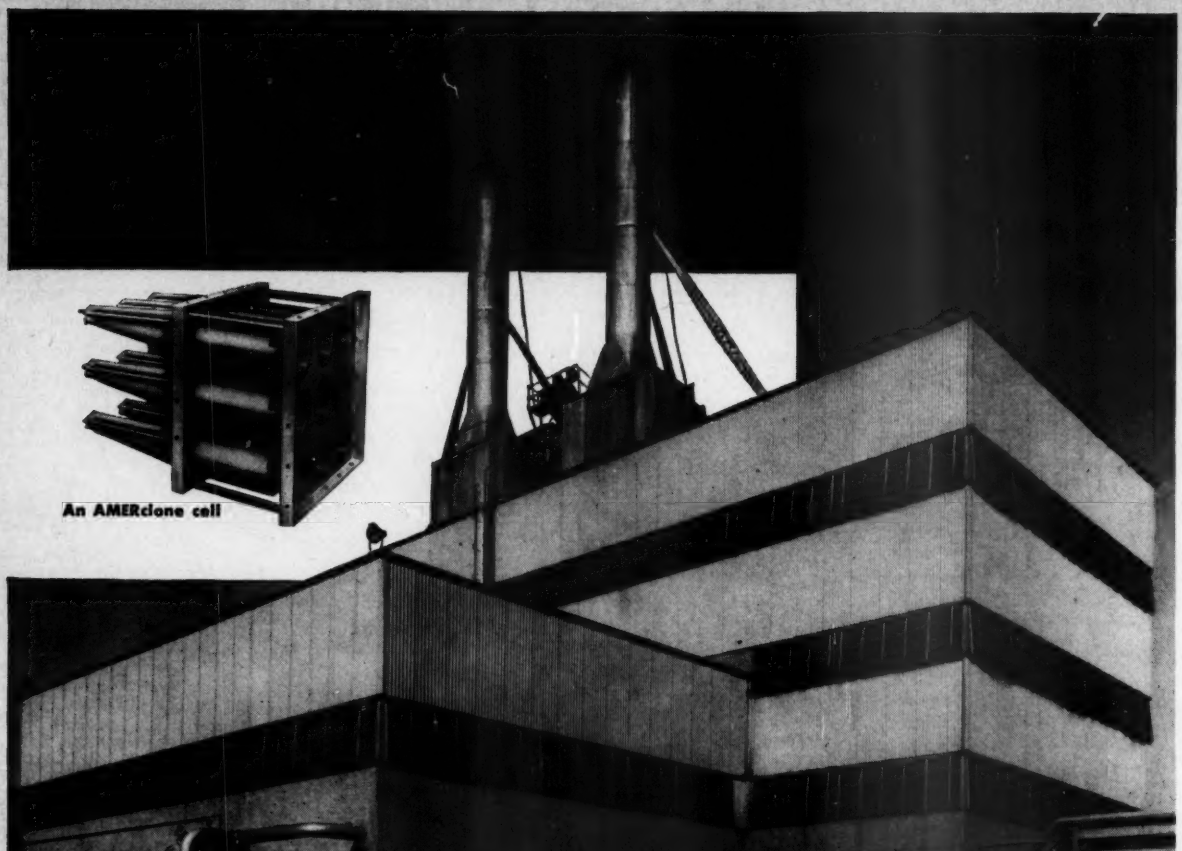


An AMERclone cell

Both of the boilers at this Southern foundry were in operation when this photograph was taken. Note absence of any visible stack effluent.

AMERclone traps 5 TONS of fly ash DAILY!

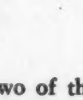
Atmospheric Nuisance Eliminated by AAF Dust Control

Boiler fly ash that formerly "went up in smoke" (only to reappear on parking lots and the surrounding neighborhood) has disappeared from the scene at this Southern foundry. An AMERclone system on each of two boilers puts this menace in its place—in the dump, where it can do no harm.

AMERclone does the job, thoroughly . . . operates at 92% efficiency *at all times,* even though boiler room requirements fluctuate as much as 30% in any 24-hour period. High collection efficiency and maintained efficiency are just two of the dollars-and-cents advantages of AMERclone. This dry centrifugal requires less space than comparable units because each 20" x 20" cell (see inset in photograph) has a rating of 3,000 cfm! And the abrasive fly ash has little or no effect on AMERclone's tough, thick-wall gray iron castings.

Don't let a few tons of dust per day stand between you and better working conditions, better community relations. Get all the facts on AMERclone. Call your local AAF representative or write direct for Bulletin 291.

AAF Filters and Precipitators



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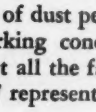

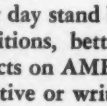

Herman Nelson Portable Heaters

Techniques of Testing for Air Contaminants From Combustion Sources*

CARL V. KANTER, ROBERT G. LUNCHE and ALBERT P. FUDURICH
Air Pollution Control District
County of Los Angeles
Los Angeles, Calif.

In any air pollution control program, the collection of factual data on the types and quantities of contaminants emitted into the atmosphere is a necessity. A basic tool for obtaining such data is source testing and this type of work is an important part of the APCD[1] program. Test data obtained are used for a number of different purposes. In the Enforcement Division, source testing data are used to check the operation of equipment for violations of certain APCD Rules. In the Engineering Division, test results are required to determine whether permits can be granted. In the Evaluation and Planning Staff, test results are used as a basis for estimating the over-all quantities of air contaminants emitted into the atmosphere. These estimates serve as a basis for determining the need of new legislation and as a guide to the form which the legislation may take. The APCD also uses source testing to evaluate the efficiency of control equipment and to determine the effects of design and operational factors on the emissions of contaminants into the atmosphere.

The Combustion Problem in Los Angeles County

Air contamination from combustion sources is a problem common to all industrialized areas. In most cities the principal combustion problem is the burning of coal. In Los Angeles, where coal is not burned, such contamination arises from incineration of refuse and from burning of fuel oil.

The APCD in the past 8 years has made more than 800 tests, including many on incinerators and power plant boilers. The techniques used in testing these combustion sources will be described. These techniques are based on principles and procedures which have been in use for many years and have been described in the literature[2,3,4]. The basic methods are generally followed in the APCD source testing work, but with some adaptations and revisions to meet special needs.

Organization

All tests are carried out by the Source Testing Section of the Research Division. Fig. 1 shows the APCD organization with the Research Division in some detail to indicate the relationship of the Source Testing Section to the other sections of the Division. The Source Testing Section with 19 engineering positions allotted for the formation of test teams, is under the direction of a Head Air Pollution Engineer. There are normally 4 test teams, but the arrangement is flexible and varies to meet a changing test schedule.

Other sections of the Research Division work closely with the test teams. The Analytical Section carries out laboratory analyses on samples collected by the test teams. The Methods Section works out new procedures for new problems. The Maintenance Section fabricates the special equipment or adapts existing equipment to the special needs of the Source Testing Section.

Requests for tests, which can originate in any part of the APCD organization, are made on the prescribed form shown in Fig. 2. All test requests are reviewed by the Evaluation and Planning Staff before they are forwarded to the Research Division for action. The review by the Evaluation and Planning Staff is made to obtain the maximum useful information per test. For example, the Enforcement Division might request a test on an incinerator for combustion contaminants[5] to determine compliance with Rule 53b[6]. The Evaluation and Planning Staff might make additions to the request to obtain information on aldehydes or oxides of nitrogen for total air pollution studies.

The operating conditions of the equipment are specified on the test request form by the person originating the request. On an incinerator these conditions might include, for example, the type of material to be burned, the burning rate, and the cycle of operation such as start up or burn down.

Arrangements For Tests

Preliminary Inspection

Prior to making any test, a preliminary inspection is made by a member of the Source Testing Section. The equipment is observed in operation and arrangements are made for the installation of necessary platforms and sampling holes. Providing these facilities is the responsibility of the management. The operating conditions to be in effect during the test are outlined, and the testing date is scheduled.

Selection of the Sampling Location

The testing of emissions from an incinerator or boiler requires the determination of the volume of gases emitted and the sampling of a representative portion of the gases in such a manner that the concentration of air contaminants may be accurately determined.

The location and number of the sampling openings in the stack should be selected so as to minimize the effects of any enlargement, contraction, entry, exit or change of direction on the flow of the combustion gases in the stack. It is commonly accepted that a straight section of stack with a length of 10 stack diameters permits a streamline flow to be established. The sampling holes must be

---

(1) The Air Pollution Control District, County of Los Angeles, Calif.

* Presented at the 49th Annual Meeting of the Air Pollution Control Association held at Buffalo, N. Y., May 20-24, 1956.

(2) Bulletin WP-50. Western Precipitation Corporation, Los Angeles, Calif.

(3) J. H. Parkin. Instruments for the Measurement of Air Velocity. *Trans. A.S.H. & V. E.*, 35, 499 (1929).

(4) Alec B. Eason. Flow and Measurement of Air and Gases. Chas. Griffin & Co., Ltd., London, England (1930).

(5) APCD Rules and Regulations. Rule 2m **Combustion Contaminants.** *Combustion Contaminants are particulate matter discharged into the atmosphere from the burning of any kind of material containing carbon in a free or combined state.*

(6) APCD Rules and Regulations. Rule 53. **Specific Contaminants.** *A person shall not discharge into the atmosphere from any single source of emission whatsoever any one or more of the following contaminants, in any state or combination thereof, exceeding in concentration at the point of discharge: (b.) Combustion Contaminants: 0.4 gr./ft.³ of gas calculated to 12% of carbon dioxide (CO_2) at standard conditions.*

AIR POLLUTION CONTROL DISTRICT—COUNTY OF LOS ANGELES

ORGANIZATION CHART

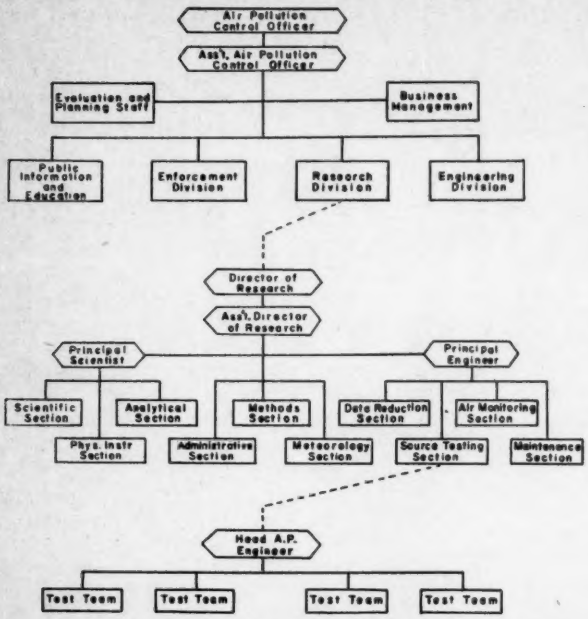

Fig. 1. Organization chart, showing divisions of APCD. Research Division is shown in some detail, to give relationship of source testing team.

AIR POLLUTION CONTROL DISTRICT - COUNTY OF LOS ANGELES
434 South San Pedro Street, Los Angeles 13, California

REQUEST FOR TEST AND/OR ANALYSIS

ORIGINATING DIVISION COPY — TEST NO.

TEST LOCATION DATA

1. Firm Name
2. Address
3. Representative to contact ... Title
4. Phone No.

REQUEST INITIATION DATA

5. Date of Request ... 6. No. of Report Copies Desired
7. Reason for Request (including APCD rules involved)
8. Request by ... Approved by (division head) ... Division

TEST INSTRUCTIONS and INFORMATION

9. Basic Equip.
10. Control Equip.
11. Point (or Points) to be tested
12. Special Instructions
13. Originating division requests analysis of the discharge for:

FOR EVALUATION AND PLANNING STAFF USE

14. Make analysis of the discharge for:
15. Remarks
16. Priority rating

RECORD OF ACTION

17. Request received by EPS on
18. Request sent to Research Division on
19. Test and analytical procedures defined and OK'd on
20. Report of Test and/or Analysis received by EPS on
21. Report approved by EPS on
22. Report sent out for interoffice distribution on
23. Report mailed to firm involved on

RESEARCH DIVISION REMARKS

16-60D24

Fig. 2. Form used whenever a test request is initiated from any division of APCD. ⟶

large enough to accommodate a Pitot tube and sampling nozzle. Their actual size depends upon the wall thickness and stack diam. For example, a thin wall stack would require a sampling hole only 2 in. diam., but a wall of 12 in. thickness would require a sampling hole approximately 6 in. in diam.

For stacks of circular cross section, 2 sets of stack traverses at right angles to each other are usually made. Thus, either 2 or 4 sampling holes, depending upon the diam. of the stack, spaced at 90° apart, are required. Two sampling holes are sufficient where stack diameters are less than the length of the Pitot tube. When the stack diam. exceeds 6 ft., it is desirable to have 4 sampling holes.

Testing Techniques

Velocity Determination

The velocities of gas flows encountered in testing combustion sources are usually in the range adaptable to measurement by Pitot tubes and inclined draft gauges. Temperatures of the gas must be determined at the same time and at the same location that Pitot tube readings are taken. A thermocouple in the stack is used for this purpose.

A standard Pitot tube is normally used, but there may be instances where plugging of the small static openings may occur. In this event, a modification of the Pitot tube may be substituted. This is constructed of a double tube with inlet openings 180° apart so that one faces upstream while the other faces downstream. A correction factor for these special tubes must be determined by calibration against a standard Pitot tube. This factor is usually about 0.8.

To obtain the average velocity in the stack, the cross sectional area of the stack is divided into a number of equal areas and Pitot readings are made at the center of each area. For circular cross section stacks, the equal areas are laid out in concentric circles. It is convenient to mark off on the Pitot tube the distances from the stack wall to the centers of each of the equal areas. Table I shows these distances as percentages of the stack diameter.

The calculated velocities are averaged and multiplied by the cross sectional area of the stack to give the gas volume.

In practice, a convenient point in the stack is selected for use as a reference point, and readings are also taken at this point when velocity traverses are made. A flue factor, which is the ratio of average stack velocity to reference point velocity is determined. Periodic readings at the reference point during the test indicate changes that occur in the volume rate of flow. The average velocity in the stack can be determined at any time by multiplying the reference point velocity by the flue factor. As changes in the velocity of the stack gases are noted, the necessary corrections are made in the sampling rate. Reference point readings should be taken at least every 5 min. during the test and as frequently as every minute if the stack gas velocity fluctuates appreciably.

Prescribed Sampling Procedure for Combustion Contaminants

For checking incinerators, boilers and other combustion equipment for compliance with existing rules, a prescribed sampling procedure for combustion contaminants has been established.

The procedure and the equipment have been selected to insure that the sample collected accurately reflects the actual stack conditions. This means that a very high collection efficiency for all particle sizes must be obtained, and gas

volume, temperature, pressure and composition must be determined with maximum precision.

A sample is withdrawn from a convenient point of near-average velocity in the stack cross section. If the flow is fairly uniform across the area, 1 sampling point is sufficient, but if the flow varies widely, it may be necessary to sample at several points to obtain a representative sample.

The sample must be withdrawn under conditions of isokinetic flow[7] to insure that the concentration of particulate matter is representative. This is accomplished by selecting a sample nozzle of proper size and maintaining a flow rate through the sampling train which will give a velocity through the nozzle equal to the stack velocity at the sampling point.

The gas velocity for each of the points measured with the Pitot tube is calculated from the relation:

$$V = 2.90\ F \sqrt{\frac{29.92}{P} \times \frac{1.00 \times HT}{D}}$$

[7] James D. Wilcox. Isokinetic Flow and Sampling. *J. Air Poll. Control Assoc.* **5**, 226 (1956).

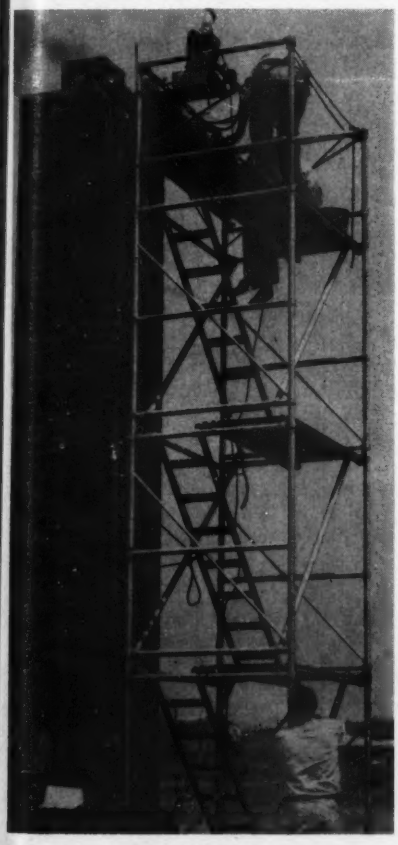

Fig. 3. Testing a multiple chamber incinerator of small size. The scaffolding is portable equipment of APCD.

TABLE I

Distance to Centers of Equal Area Zones for Velocity Traverse
% of Stack Diam. From Circumference to Test Point

Point No.	Number of Areas				
	2	3	4	5	6
1	6.2	4.4	3.3	2.2	2.0
2	25.0	14.7	10.5	8.2	6.7
3	75.0	29.4	19.5	14.5	11.8
4	93.8	70.6	32.1	22.7	17.7
5		85.3	67.9	34.4	25.0
6		95.6	80.5	65.6	35.4
7			89.5	77.3	64.6
8			96.7	85.5	75.0
9				91.8	82.3
10				97.8	88.2
11					93.3
12					98.0

where

V = Velocity, ft./sec.
F = Pitot tube factor ($F = 1.0$ for the standard Pitot tube)
P = Stack gas pressure, in. of mercury absolute
D = Specific gravity of stack gas referred to air ($D = 1$ for combustion gases)
H = Draft gauge reading, in. of water
T = Stack gas temperature, degrees F. absolute

The required rate of flow through the meter for a given nozzle diam. is obtained from the following relation:

$$M = \frac{\pi d^2}{4 \times 144} \times V \times 60 \times \frac{Tm}{Ts}$$

$$= 0.33 \frac{Tm}{Ts} V d^2$$

where

M = Meter rate, ft.³/min.
Tm = Temperature in meter, degrees F. absolute
Ts = Temperature in stack, degrees F. absolute
V = Velocity of stack gases, ft./sec.
d = Diam. of sampling nozzle, in.

The sampling train consists of a sampling nozzle, 3 impingers[8,9,10] in series in an ice bath, a weighed paper thimble, dry gas meter, and pump, all connected as shown in Fig. 5. A glass tube bent to point into the gas flow may serve as the sampling nozzle and is used when the stack temperature does not exceed 900°F. The sampling rate for this train may range from ½ to 1 ft.³/min.

Fig. 4. Taking Pitot tube readings at top of stack. It is preferable to have location of Pitot traverse well below top of stack when possible, to minimize the errors resulting from non-uniform velocities at the outlet.

The first 2 impingers in the train each contain 100 ml. of distilled water and the third impinger is dry with a thermometer attached to the stem.

During the sampling, the Pitot tube and thermocouple are inserted into the stack at the reference point. The following readings are taken at least once every 5 min. for the duration of the test:

1. Meter reading (also taken at start and end of run).
2. Meter vacuum.
3. Gas temperature at meter.
4. Temperature in third impinger.
5. Pitot tube draft gauge.
6. Stack temperature.

The impingers serve to cool the stack gas sample, to collect particulate matter,

[8] L. Greenburg and G. W. Smith. A New Instrument for Sampling Aerial Dust. *U. S. Bur. Mines, R. I.* 2392 (1922).

[9] J. J. Bloomfield and J. M. Dalla Valle. The Determination and Control of Industrial Dust. *Pub. Health Bull.* 217 (1935).

[10] J. M. Dalla Valle. Note on Comparative Tests Made With the Hatch and the Greenburg-Smith Impingers. *Pub. Health Repts.* (U. S. Public Health Service) **52** 1114 (1937).

Fig. 5. Prescribed sampling train for combustion contaminants. The first two impingers following the glass sampling tube contain water but the third one is dry. A paper thimble, meter and pump complete the sampling train.

Fig. 6. Impingers and holder. The holder also serves as an ice bath. The third impinger, which is used dry, has a thermometer attached to its inner stem for use in estimating the water vapor content of the metered gas after its saturation in the wet impingers.

and to condense moisture from the gases before they pass through the paper thimble. The thimble collects any particulate matter which may pass through the impingers.

The duration of the sampling is normally 1 hr., but in some cases the operating conditions encountered may require a longer or shorter time for sampling.

Sampling for Carbon Dioxide

Under the provisions of Rule 53b[5], the concentration of combustion contaminants must be calculated to 12% carbon dioxide. This gives a standard basis for all types of combustion operations, and insures against circumvention of the Rule by dilution. Thus on all tests for combustion contaminants, it is necessary to determine the average carbon dioxide concentration for the period of sampling.

An integrated gas sample for Orsat analysis is collected by withdrawing gases continuously from the stack at a constant rate by a liquid displacement method. As shown in Fig. 7, a 5-*l.* bottle filled with a saturated sodium sulfate solution, acidified with sulfuric acid, is used as the collecting gas holder. As the solution siphons out, the gas sample is drawn into the bottle. The rate of siphoning is adjusted so that a gas sample of about 4 *l.* is obtained during the course of the test. The sample is drawn from the stack at the same cross section used for collecting the combustion contaminants.

Measuring the Combustion Contaminant Sample

At the end of the sampling period the sampling train is disconnected, and all the collection apparatus is stoppered and returned to the laboratory for analysis.

The paper thimble is dried in a constant temperature oven for 30 min. at 105°C. and allowed to condition in the balance room before being weighed. A

[5] See Footnote 5, page 191.

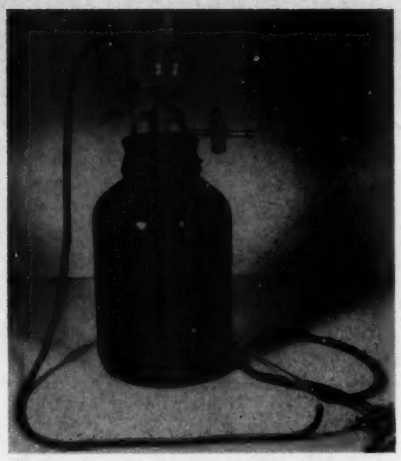

Fig. 7. Bottle for collecting sample for CO_2 determination. Contains acidified sodium sulfate solution. Gas is drawn in during siphoning out of solution. After gas sample is collected, solution in funnel is allowed to flow down to maintain a pressure in the bottle slightly above atmosphere.

weighed control thimble is treated similarly, so that a correction may be applied to the sampling thimble for any change of weight which may occur because of humidity changes in the balance room atmosphere.

The solution in the impingers is volumetrically measured. An increase in volume occurs because of condensation of moisture from the stack gases. This must be taken into account when calculating the sample volume.

The contents of the impingers and connecting tubing are carefully washed into a beaker and slowly evaporated to a vol. of 20 to 30 ml. This is transferred quantitatively to a weighed 50 ml. beaker, and evaporated to dryness at 105°C. in an oven. The beaker is cooled in a desiccator and weighed.

The total weight of combustion contaminants is the sum of the weights of material collected in the impingers and the thimble.

The volume of flue gases sampled is the difference in initial and final meter readings plus the volume calculated from the water condensed in the impingers. This moisture volume is obtained as follows:

$$W = \frac{C}{453.6} \times \frac{379}{18} \times \frac{T_m}{520} \times \frac{29.92}{(P_a - P_m)} = 0.00267\, C\, \frac{T_m}{P_a - P_m}$$

where

W = Vapor vol. of condensed moisture at meter conditions, ft.^{3}
C = Vol. of condensed water, ml.
T_m = Temperature in meter, °F. absolute
P_a = Atmospheric pressure, in. of mercury
P_m = Meter vacuum, in. of mercury

Fig. 8. Alundum thimble and holder. From left, sampling nozzle, cap with heat resistant gasket, alundum thimble with glass wool plug, spring and holder, thimble housing.

Fig. 9. Sampling train using miniature glass cyclone, alundum thimble, and impingers. Meter and pump complete the train.

The combustion contaminants are reported as gr./scf. calculated to 12% carbon dioxide.

Alternate Sampling Trains for Particulate Matter

In many cases, tests are run to obtain information about the particulate matter being emitted from a combustion process when the question of compliance with existing rules is not involved. In addition to grain loadings, it may be desirable to make particle size determinations, microscopic studies, or chemical analyses. In these cases, other sampling trains more suitable to the desired purposes may be used.

In one train, an alundum thimble is placed before the impingers so that the particulate matter is collected in a dry state (Fig. 8 and 9). Very fine particulate matter will usually pass through the alundum thimble and be collected in the impingers. The weights of the material collected are obtained in a manner similar to that described for the prescribed sample train.

A miniature glass cyclone has been used in front of the thimble (Fig. 9) on a number of tests to separate out the particulate matter above 5 μ. Fig. 10 is a photograph of the cyclone, and Fig. 11 is a schematic drawing showing the design dimensions.

Another sampling train used on occasion consists of an electrical precipitator followed by an impinger train. The Source Testing Section has found that this equipment, because of its additional weight, space requirements and special handling, is not feasible for the testing of some sources.

Sampling and Analysis for Other Contaminants

It is often desirable to test for certain specific contaminants emitted from com-

Fig. 10. Miniature glass cyclone, with ground glass joints. Constructed to specified design dimensions within close tolerances.

bustion processes. A few of these are listed below, with a brief description of the method for sampling and analysis.

Sulfur Dioxide and Sulfur Trioxide

The sampling train for sulfur dioxide and sulfur trioxide consists of a paper thimble *maintained just above the dew point of the stack gases* followed by 3 series-connected impingers immersed in an ice bath, a dry gas meter and a pump. The thimble acts as a collector for the sulfuric acid aerosol formed from the sulfur trioxide. The first 2 impingers contain 100 ml. each of approximately 5% sodium hydroxide solution. The third impinger is dry. The sulfur dioxide gas passes through the thimble and is collected in the impingers.

The thimble is extracted with hot water and the solution is titrated with standard sodium hydroxide solution to determine the sulfur trioxide. The sulfur dioxide collected in the impingers is determined by oxidation with bromine, acidification, and precipitation as barium sulfate.

Ammonia

The sampling train for ammonia consists of 3 series-connected impingers immersed in an ice bath followed by a dry gas meter and a pump. The first 2 impingers contain 100 ml. each of approximately 5% hydrochloric acid solution. The third impinger is dry.

The ammonia is determined by a modified Kjeldahl distillation method. An excess quantity of sodium hydroxide is added to the impinger solution and the ammonia is distilled into a measured volume of standard acid. The excess acid is titrated with a standard base to obtain the ammonia content.

Ammonia is not normally found in the flue gases from combustion sources. Tests for ammonia are made only in special cases where its presence might be suspected. For example, it has been found that flue gases from catalytic cracking regenerators contain ammonia.

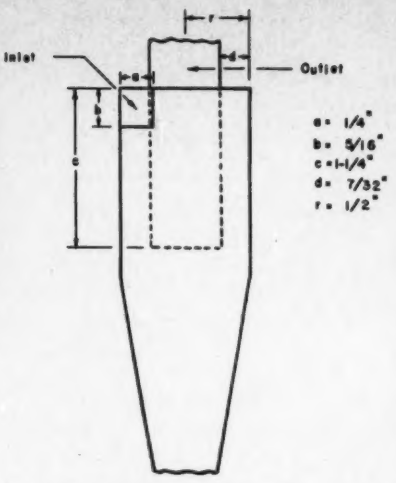

Fig. 11. Miniature glass cyclone. Line drawing showing design dimensions.

Organic Acids

The sampling train for organic acids consists of 3 series-connected impingers followed by a dry gas meter and a pump. The first 2 impingers contain 100 ml. each of a 5% sodium hydroxide solution and the third impinger is dry.

The impinger solution is acidified to a pH of 2 and is extracted with ether in a liquid-liquid extraction apparatus. Water is added to the extract and the mixture is titrated with standard sodium hydroxide solution to the phenolphthalein end point.

Hydrocarbons, Aldehydes, Oxides of Nitrogen

Samples for the determination of hydrocarbons, aldehydes, and oxides of nitrogen are collected in evacuated bulbs (Fig. 12). At least 4 samples for each of the gases are taken during a 1 hr. test period. The bulbs for hydrocarbon samples are used dry; for aldehyde samples they contain sodium bisulfite absorbing solution; and for oxides of nitrogen they contain a mixture of hydrogen peroxide and 0.1 N sulfuric acid.

The hydrocarbons are determined by an infrared spectrophotometer and the results are expressed as hexane[11]. The aldehydes are determined by a modified Ripper's method[12] and are expressed as formaldehyde.

The oxides of nitrogen are determined by the phenol disulfonic acid method

[11] P. P. Mader, M. W. Heddon, R. T. Lofberg, and R. H. Koehler. Determination of Small Amounts of Hydrocarbons in the Atmosphere. *Anal. Chem.* **24**, 1899 (1952).

[12] F. H. Goldman, and H. Yagoda. Collection and Estimation of Traces of Formaldehyde in Air. *Ind. & Eng. Chem. Anal. Ed.* **15**, 377 (1943).

Fig. 12. Grab Sample Bulbs. Above, 2 l. Bulb. Scotch tape covering is for safety. Below, 300 ml. sampling tube with ground glass stopcocks.

[13,14,15] and reported as nitrogen dioxide. Both the nitric oxide and nitrogen dioxide which may be present are measured by this method.

Sample Calculations

In the preparation of an APCD test report, summary sheets, as shown in Fig. 13 through 18 are used for the recording of test data and conditions and for showing the calculations, results and sampling trains. Pertinent data from an actual test on a municipal incinerator have been selected and will be used to demonstrate step-by-step the calculations made for the test.

Data for Calculations

Stack diam.	78	in.
Stack area	33.2	$ft.^2$
Pressure in stack	29.9	in. Hg.
Temperature in stack	319	°F.
Sampling nozzle diam.	12	mm.
Meter vacuum (average)	5.5	in. Hg.
Meter temperature (average)	67	°F.
Metered sample volume (at meter conditions)	21.7	$ft.^3$
Vol. of water vapor condensate	100	$cm.^3$
Vapor Pressure of water at impinger temperature	0.7	in. Hg.
Type Pitot tube used		Standard
Orsat analysis (on a dry basis)	79.7	% N
	6.9	% CO_2
	13.4	% CO_2

[13] J. Glater. The Determination of Oxides of Nitrogen by the Phenol Disulfonic Acid Procedure. *Chemical Methods Notebook APCD* (1953) (Unpublished).

[14] R. L. Beatty, L. B. Berger, and H. H. Schrenk. Determination of the Oxides of Nitrogen by the Phenoldisulfonic Acid Method. *U. S. Bur. of Mines R. I.* 3687 (1943).

[15] M. B. Jacobs. Analytical Chemistry of Industrial Poisons, Hazards and Solvents. Interscience Publishers, Inc. N. Y., p. 354 (1949).

AIR POLLUTION CONTROL DISTRICT - COUNTY OF LOS ANGELES

SUMMARY SHEET

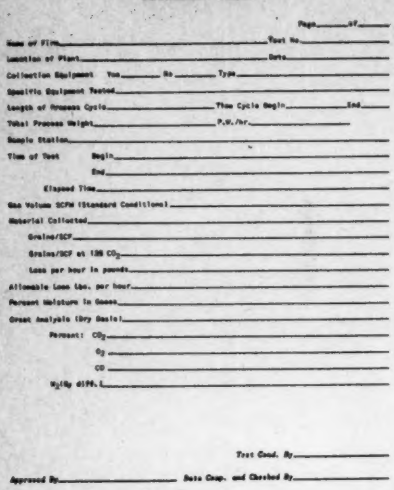

Fig. 13.

Velocity head at sampling point 7	0.03	in. H_2O
Temperature at sampling point 7	320	°F.
Average reference point velocity before test	13.8	ft./sec.
Average stack velocity before test	12.8	ft./sec.
Average reference point velocity during test	14.2	ft./sec.
No. of equal traversing areas in stack	6	
No. of sampling points	12	
Net weight of particulate matter collected	0.151	gm.

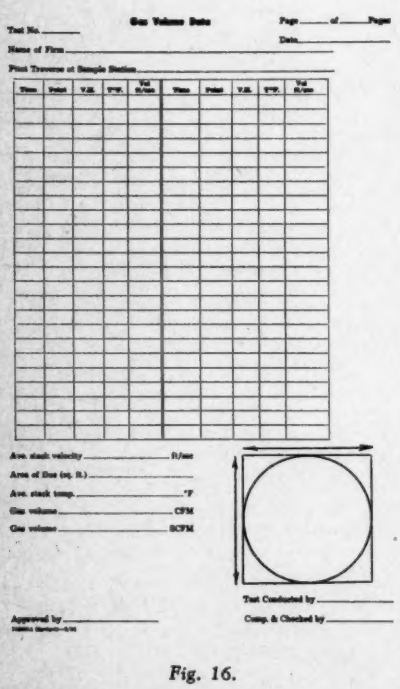

Fig. 16.

AIR POLLUTION CONTROL DISTRICT - COUNTY OF LOS ANGELES

SUMMARY OF CALCULATIONS

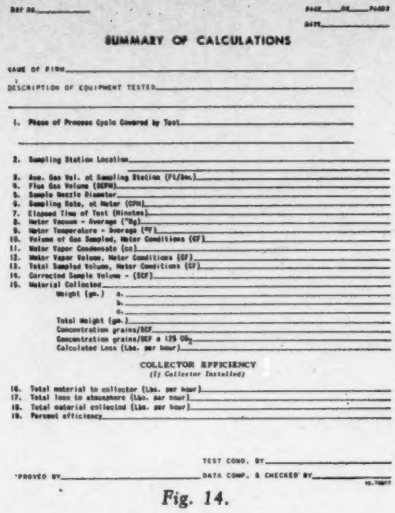

Fig. 14.

Traverse Points

Before testing can begin or any Pitot tube traverses can be made, the traverse points must be selected. For a circular stack of 78 in. diam., it is advisable to divide the stack cross section into 6 equal concentric areas. Points along the 2 traverse diam. at right angles to each other at which readings should be taken fall on the circles dividing each of the equal areas into 2 smaller equal areas. The distances from the stack circumference to each of the successive points along a diam. are calculated from Table I which gives the required distances in terms of a percentage of the diam. For example, in this case of a stack divided into 6 equal areas, point 6 is a distance in from the stack circumference of 35.4% of the diam., or *Distance to Pt. 6 = 0.354 x 78 in. = 37.6 in. from stack circumference.*

AIR POLLUTION CONTROL DISTRICT - COUNTY OF LOS ANGELES

CALCULATION SHEET

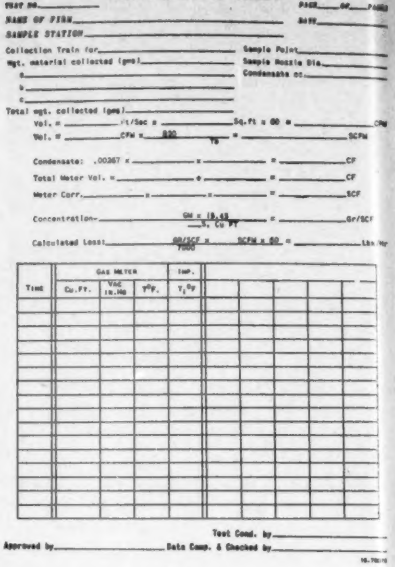

Fig. 15.

Velocity at a Traverse Point Before Sampling

At this stage of the test, velocity head readings are taken with the Pitot tube and inclined differential pressure gauge at various traverse points. Although the density of the gas is not yet known, it can be assumed to be the same as air and any correction for difference from air can be made later. The relationship between the velocity of the gas and the velocity head reading is

$$V = 2.90\,F\,\sqrt{\frac{29.92}{P}}\;x\;\frac{1.00}{D}\;x\;HT$$

$$V = 2.90 \times 1.0 \times \sqrt{\frac{29.9}{29.9}}\;x\;\frac{1.00}{1.00}\;x\;0.03\,(460 + 320) = 14.0\ ft./sec.$$

AIR POLLUTION CONTROL DISTRICT - COUNTY OF LOS ANGELES

CALCULATIONS

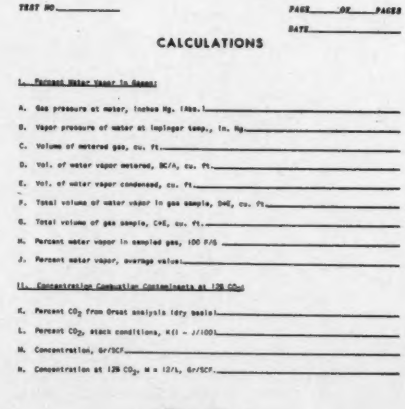

Fig. 17.

SAMPLING APPARATUS

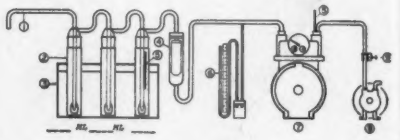

Fig. 18.

1. Sample Probe
2. Impinger (Dust Concentration Sampler)
3. Ice Bath Container
4. Dry Filter
5. Thermometer
6. Mercury Manometer
7. Sprague Dry Gas Meter (Zephyr No. 1A)
8. Vacuum Pump
9. Hose Clamp to Control Gas Flow Rate
10. Impinger Solution

TABLE II

Incinerator Test Results

Type of incinerator[a]	SB	SC	FF	MI	MI	MM	MM
Type of material burned[b]	P, WP, C	P, M, C	P, WP, C, M, G	P, C, W, L	P, W	P, WP, C, GR, M, W, TT, F	P, WP, C, GR, G, W, TT
Rated capacity—(lbs./hr.)	25	—	—	1500	6000	6000	9400
Test burning rate—(lbs./hr.)	28	60	68	2000	6180	5390	8580
CO_2 in stack gas—(Dry basis)—(%)	2.3	5.2	3.3	5.3	1.2	6.3	6.2
Moisture in stack gas—(%)	4.6	6.5	9.1	6.8	11.6	15.7	27.5
Vol. of stack gas—(scf./lb. burned)	700	144	846	125	226	189	115
Grain loading—(gr./scf.)	0.117	0.75	0.196	0.104	0.104	0.106	0.246
Particulate matter—(lbs./ton burned)	23.4	31.0	47.3	3.7	3.4	5.7	8.11

[a]Type of Incinerator

SB=Small single chamber, backyard-type
SC=Single chamber, commercial-type
FF=Flue-fed, unmodified, apartment house
MI=Multiple chamber, industrial-type
MM=Multiple chamber, municipal-type

[b]Type of Material Burned

P=Paper
C=Cardboard
G=Garbage
GR=Grass cuttings
TT=Tree trimmings
W=Wood
F=Fish paper
WP=Waxed paper
M=Milk cartons
L=Leather, rubber or plastics

Flue Factor

When the velocities have been calculated for all of the traverse points and the reference point, the flue factor is determined from the ratio of the average velocity to the reference point velocity.

$$\text{Flue Factor} = \frac{\text{Average Velocity}}{\text{Reference Point Velocity}} = \frac{12.8}{13.8} = 0.927$$

Thus by taking Pitot tube readings at the reference point at regular intervals throughout the test and applying the flue factor to the resulting calculated velocity, the average stack velocity is obtained. Adjustments are then made, if necessary, to the sampling rate for changes noted in the velocity so as to maintain isokinetic sampling conditions.

Sampling Rate, Dry Gas Basis, Meter Conditions

Once the velocity at the proposed sampling point has been determined, the sampling rate (meter rate) to be used for isokinetic flow conditions is estimated. A sampling nozzle is chosen which will give a rate of ½ to 1 cfm. for the velocity measured at the sampling point. The relationship between the sampling rate, velocity and nozzle diam., as shown previously, is:

$$M = 0.33 \frac{T_m}{T_s} Vd^2$$

For a nozzle diam. of 12 mm.:

$$M = 0.33 \left(\frac{460 + 67}{460 + 319}\right)(13.8)\left(\frac{12}{25.4}\right)^2 = 0.69 \text{ cfm.}$$

Because some of the moisture in the stack gases is condensed before reaching the meter, a correction to the above meter rate should be made. Experience from previous tests can be used to estimate the moisture content of the stack gases which will condense before reaching the meter. As an example, to show how this correction can be handled, a moisture content of 20% for this type of combustion source is assumed. The meter rate, taking into account the moisture correction, would be:

$$0.69\ (1 - 0.20) = 0.55 \text{ cfm.}$$

A further correction to the meter rate involves the effect of the negative pressure in the meter on the sample vol. This correction can be applied by noting the meter vacuum and multiplying the estimated meter rate by the ratio of the stack pressure to meter absolute pressure. Since the meter vacuum varies with the sampling rate, several calculations may have to be made. As an example, use a meter vacuum of 5.5 in. of mercury and get the corrected meter rate of:

$$0.55 \times \left(\frac{29.9}{29.9 - 5.5}\right) = 0.68 \text{ cfm.}$$

Gas Volume of Condensed Water

The gas vol. of the condensed water is related to the liquid vol. of the condensate collected in the impingers as shown previously:

$$W = 0.00267\ C \frac{T_m}{(P_a - P_m)}$$

and for the test conditions:

$$W = 0.00267 \times \frac{100\ (460 + 67)}{(29.9 - 5.5)} = 5.8 \text{ ft.}^3$$

Water Vapor Vol. in the Metered Sample

This value is calculated based on the assumption that the sampled vol. measured by the meter is saturated with water vapor at the temperature in the third impinger.

$$W_V = \left(\frac{V.P.}{P_a - P_m}\right) \times V_m$$

where

W_V = Water vapor vol. in metered sample, ft.³
$V.P.$ = Vapor pressure of water at impinger temperature, in. Hg.
P_a = Atmospheric pressure, in. Hg.
P_m = Meter vacuum, in. Hg.
V_m = Metered vol. of sample

and for the test data:

$$W_V = \left(\frac{0.7}{29.9 - 5.5}\right) 21.7 = 0.6 \text{ ft.}^3$$

Vol. % of Moisture in Stack Gases

$$\text{Vol. \% Moisture} = 100\left(\frac{W + W_V}{W + V_m}\right) = 100\left(\frac{5.8 + 0.6}{5.8 + 21.7}\right) = 23.3\%$$

Specific Gravity of Gas

The specific gravity of the stack gases *referred to air* is a factor in the calculation of velocity from a Pitot tube traverse. Generally neither the density of the gas nor its composition is known before or during the test, unless previous tests have been made of the same source. Stack gases from combustion sources can usually be considered as having specific gravities close to 1.0 in order to make the preliminary velocity calculations. After the test has been completed, the results of an Orsat analysis on a dry basis can be converted to a wet basis and used for estimating the specific gravity of the gas as follows:

Component	Mol. Fraction of Component		Molecular Weight		Lb. of Component/ Mol. of Gas
H_2O	.233	x	18	=	4.19
CO_2	(1.000 − .233) (0.069)	x	44	=	2.33
O_2	(1.000 − .233) (0.134)	x	32	=	3.29
N_2	(1.000 − .233) (0.797)	x	28	=	16.04
	Molecular Weight of Sample			=	25.85

and the specific gravity compared to air is:

$$\frac{25.85}{28.95} = 0.89$$

The correction factor, S, to be applied to velocities and stack gas volumes is:

$$\sqrt{\frac{1.00}{0.89}} = 1.06$$

Gas Sample Vol.

Vol. at meter conditions
$= W + Vm$
$= 5.8 + 21.7$
$= 27.5$ *ft.³ at meter conditions*

Vol. at standard conditions

$$= 27.5 \times \left(\frac{460 + 60}{Tm}\right) \times \frac{Pa - Pm}{29.92}$$

$$= 27.5 \times \frac{460 + 60}{460 + 67} \times \frac{29.9 - 5.5}{29.9}$$

$= 22.2$ *scf.*

Grain Loading

The grain loading is the ratio of the weight of the total particulate matter collected to the gas sample volume expressed in gr./scf. In this test, the value is:

$$\frac{0.151 \text{ gm.} \times 15.43 \frac{\text{gr.}}{\text{gm.}}}{22.2 \text{ scf.}} = 0.105 \text{ gr./scf.}$$

Total Stack Gas Volume at Standard Conditions

This volume is calculated from the product of the average velocity obtained during the test and the stack area, with factors for specific gravity, temperature and pressure. The velocity is converted from ft./sec. to ft./min.

$$Vol. = V_R \times f \times S \times A \times \frac{520}{T} \times \frac{P}{29.90} \times 60$$

where

V_R = Average velocity at reference point during test, ft./sec.
f = Flue Factor
A = Specific gravity correction
T = Area of stack cross section, ft.²
S = Temperature of stack gas, °F. absolute
P = Pressure of stack gas, in. of Hg.

and for this test:

$$Vol. = 14.2 \times 0.927 \times 1.06 \times 33.2 \times \frac{520}{779} \times \frac{29.9}{29.9} \times 60 = 18{,}600 \text{ scfm.}$$

Mass Rate of Emission

The loss of particulate matter in lbs./hr. is obtained from the gr. loading and the stack gas vol.

$$Loss = \frac{0.105 \frac{\text{gr.}}{\text{scf.}}}{7000 \frac{\text{gr.}}{\text{Lb.}}} \times 18{,}600 \text{ scf.} \times 60 \frac{\text{min.}}{\text{hr.}} = 16.7 \frac{\text{lb.}}{\text{hr.}}$$

The calculation of the grain loading at 12% carbon dioxide is made by the APCD to determine compliance with Rule 53b. The measured carbon dioxide concentration (dry basis) must be corrected to a wet basis.

% CO_2 (dry basis) = 6.9
% H_2O in stack gases = 23.3
Gr. loading = 0.105 gr./scf.

CO_2, wet basis = (1.000 − 0.233) x 6.9
= 5.3%

Gr. loading corrected to

$$12\% \ CO_2 = \frac{12}{5.3} \times 0.105 = 0.238 \frac{\text{gr.}}{\text{scf.}}$$

Analytical Results

Tables II and III are included to show typical results which have been obtained from the testing of incinerator and boiler installations.

The results of spectrographic and chemical analyses may be expected to vary with the material being burned. Table IV indicates values which have been found in these types of tests.

Conclusions

In most air pollution control studies of combustion sources, attention has been largely focused on the amount of particulate matter discharged. In the testing program of the APCD, methods for measuring other contaminants in the gaseous state have been established. These methods have been described briefly with the anticipation that they may be of use

TABLE IV

Spectrographic and Chemical Analyses

COMPOSITION OF PARTICULATES—% by Weight

Component	From Multiple Chamber Incinerators		Component	From Boiler
Aluminum	1.2	0.34	Free Carbon	63.2
Boron	0.32	0.32	Ether Soluble Volatiles	2.3
Calcium	0.92	0.50	Aluminum Oxide	1.65
Chromium	0.14	3.7	Barium "	0.38
Cobalt	0.0015	0.026	Boron "	0.012
Copper	0.13	0.015	Calcium "	0.22
Iron	1.8	19.5	Chromium "	0.063
Lead	0.33	0.11	Cobalt "	0.085
Magnesium	1.3	1.0	Copper "	0.012
Manganese	0.18	0.11	Iron "	3.15
Molybdenum	0.0093	0.003	Lead "	0.11
Nickel	0.16	2.8	Magnesium "	0.17
Potassium	Trace	—	Manganese "	0.043
Silicon	12.0	2.7	Molybdenum "	0.017
Silver	0.016	—	Nickel "	1.78
Sodium	Trace	—	Sodium "	0.90
Tin	0.031	0.020	Strontium "	0.042
Titanium	0.022	0.0099	Titanium "	0.029
Vanadium	0.0012	0.014	Vanadium "	2.54
Zinc	3.2	0.51	Phosphoric Anhydride	0.89
Zirconium	0.010		Sulfuric "	17.5
			Silica	0.56

GASEOUS CONTAMINANTS—lbs./ton burned

Contaminant (Lbs./ton Burned)	Sgl. Ch. Incin.		Boilers		
			Gas[d]	Oil	Oil
Sulfur dioxide	2.3	1.4	0.2	78	57.74
Sulfur trioxide	nil	0.5	nil	0.14	0.074
Nitrogen oxides	3.9	4.6	51.5	56.09	10.0
Organic acids[a]	2.0	3.9	0.2	0.81	0.47
Aldehydes[b]	0.03	2.7	5.4	1.30	nil
Hydrocarbons[c]	nil	nil	—	0.19	0.56
Acetylene	—	—	—	0.06	nil
Ammonia	0.33	0.5	—	—	—

[a] Organic acids expressed in terms of acetic acid

[b] Aldehydes expressed in terms of formaldehyde

[c] Hydrocarbons expressed in terms of hexane.

[d] 165 lb./100,000 ft.³ burned.

TABLE III

Test Results For Power Plant Boilers

Type of boiler Type of fuel burned	Water tube Oil—4° A.P.I. 1.6% sulfur	Water tube Oil—8.7° A.P.I. 1.4% sulfur	Water tube Natural gas
Rated capacity—lb. steam/hr.	1,140,000	850,000	500,000
Test fuel burning rate			
Oil—tons/day	990	732	—
Gas—ft.³/hr.	—	—	615,000
Vol. of stack gas—scfm.	438,000	265,000	166,000
CO_2 in stack gas—% (dry basis)	9.9	8.6	7.4
Moisture in stack gas—%	8.5	7.8	—
Grain loading—gr./scf	0.0544	0.0344	0.0068
Particulate matter—			
lbs./ton burned	4.96	2.56	—
lbs./100,000 ft.³ burned	—	—	1.56
lbs./hr.	203	78.1	9.6

to other agencies investigating air contamination from combustion sources.

The APCD has a development program to improve methods and apparatus for field testing. The most important consideration in this work is reliability of results, and new developments must equal or exceed the present methods in this respect. If simplified methods can be developed, they will accelerate testing programs so that data vitally required for air pollution studies can be accumulated more rapidly.

In addition to simplification, standardization is needed so that test results and air pollution statistics compiled in different communities may have a uniform basis for comparison.

Incinerator Testing and Test Results*

F. R. REHM

County of Milwaukee

Milwaukee, Wis.

Few people in the air pollution control field will deny the significant contribution of domestic, commercial and municipal incinerators to the overall air pollution problem of our urban communities. Yet, in spite of this acknowledged importance of the incinerator in the field of air pollution control, little quantitative evaluation of incinerator effluents has been made. Partly responsible for this condition is the lack of clearly defined limits of emission that apply specifically to incinerator effluents. But more generally the reason for the lack of quantitative evaluation in this field is the great deal of special equipment required, the special effort and time demands, and the detailed nature of the test procedures and calculations involved. Quantitative evaluation of incinerator effluents applies primarily, under existing air pollution laws and regulations to the particulates evolved. There is no easy way to estimate or predict flyash or dust emission without the benefit of an actual exit dustloading test. Seldom, except in the disposal of certain highly flammable materials, is visual smoke an appreciable factor in incinerator operation. This is particularly true of the domestic and the municipal incinerator where the characteristic charge material is of a less flashy or volatile nature, as incinerator feed material goes. We are all aware of the vagaries in the use of the Ringelmann Chart as a quantitative device for evaluating visual smoke emission. As for another objectionable emittant in incinerator operation—that of odor, it appears that considerable time will lapse before we learn the actual constitution or makeup of odors, aside from setting up quantitative limitations for its control. This, of course, leaves only the field of particulate emission where scientific quantitative evaluation is possible. Fortunately, it is in the field of particulate emission that the greatest control effort is needed. The primary source of incinerator compliants lies in the realm of particulate emission.

Almost all smoke regulation or air pollution ordinances in the country contain some provision for the limitation of flyash and dust emission. Like many of the other major cities of the country, the County of Milwaukee limitation on dust emission is the recommended ASME limitation of 0.85 lb. dust/1000 lb. flue gas, adjusted to a 12% carbon dioxide (CO_2) basis or a 50% excess air basis. It is not our intention at this time to discuss the merits or shortcomings of applying this limitation to incinerator effluents. We are all aware that this limitation was developed and aimed primarily at a solid-fuel fired, steam power plant. In the absence of other limitations specifically denoted for incinerator effluents, this, or a similar type limitation, presently constitutes the only legal limits now in effect. Without entering the area of controversy as to whether the recommended ASME dust limitation should be applied to incinerators, or whether it is too lax or too strict, we can say after considerable dust test experience on incinerators of *all* sizes that a properly designed, engineered and operated incinerator *can* be made to comply with this limitation.

The testing of particulate emission from an incinerator of any size, from a domestic to a municipal unit, presents some special problems peculiar to this activity. In the first place, there are only 2 fairly uniformly accepted dust testing guides now available. These are the ASME *Test Code for Dust-Separating Apparatus* and Western Precipitation Corporation's Bulletin WP-50 *Gas and Dust Measurements*. While both codes or guides are meant to cover a broad field of application, it is quite obvious that in one case the Test Code (ASME) was written specifically to cover steam power plant testing, and in the other

* Presented at the 49th Annual Meeting of the Air Pollution Control Association held at Buffalo, N. Y., May 20-24, 1956.

instance the bulletin was written with regard to testing with some specific apparatus and the use of test methods and devices which best suited this particular test equipment. Both are well written and in general are excellent guides or codes on the general subject of dust testing. Neither of these 2 test codes except by inference, however, point to some of the main problems in incinerator testing. Let us at this point repeat that by incinerator testing, we are referring to particulate testing only.

Of the 2 publications mentioned, we feel that the ASME *Test Code for Dust-Separating Apparatus (1941)* currently offers the best type of guide lines which will permit the most effective testing of incinerators within the existing air pollution laws and regulations. This statement is predicated upon the knowledge gained in well over 260 dust tests performed to date. The 2 main reasons for making this statement stem from: (1) the nature of the incinerator effluents involved and (2) by virtue of the wide fluctuations in operating conditions necessitated by the presently used methods of incinerator charging and operation.

(1) Discussing the first reason above further points up a fundamental question in the setting of dustloading limitations and in dust testing itself. In order to have valid results in reporting a dust-loading test, it is necessary to have a *truly* representative sample of the gas and the suspensoids in question. Acquiring such a representative sample is one of the most difficult and controversial phases of any test method. Where the dust or particulate involved is a homogenous type material of uniform particle size, shape and density and where the dust and sampling conditions in the field present uniform dust distribution conditions, the problems of dust testing are greatly simplified. But where the particle size, shape and density of the effluent particulates vary as in the case of incinerators from sub-μ to the size, shape and density of char or flake particles, then the problem of representative sampling does become acute. This is particularly true of the sampling of the larger-sized particles which constitute the bulk of the total weight of the entrained particulates of incinerator effluents. This consideration has caused us to abandon any further attempt to utilize the small volume sampling train (1 to 2 cfm.) advocated by some people as a satisfactory test apparatus. Such volumetric sample limitations impose a maximum sample nozzle diam. of 1/4 in. or so, in order to maintain isokinetic sampling conditions in the duct or stack with conventional incinerator design stack or duct velocities. The fallacy of using this size sampling nozzle must be obvious to any control officer who has examined incinerator discharges and effluents. It is very common to collect char or flake material in incinerator discharges in our present field sampling equipment in the 3/8 in. to 1/2 in. size range. We have caught char or flake particles in our test apparatus up to 7/8 in. in diam. in our commercial, industrial and municipal incinerator test program. It is these larger-sized particles (in the visual range) that constitute the major part of the air pollution problem within the framework of existing codes or regulations. Someday we may put greater emphasis in our control programs on the sub-μ particles evolved, but at present our control efforts must be directed at the larger particulates which offer the greatest *nuisance pollution potential*. As long as quantitative control regulations are put on a weight or dustloading basis, and do not take into account such factors as soiling power, respiratory or inhalation hazard, toxicity, *etc.* we must of necessity put the greatest emphasis on particulates in the visual size ranges. This requires that large diam. sampling nozzles be used and that large sampling volumes be taken in incinerator testing. It is our practice to utilize sampling nozzles ranging from 1 1/4 to 2 in. inside diameter depending on stack or duct velocity. These diameters permit the taking of gas samples ranging from 15 to 27 cfm. at stack or duct conditions.

(2) The WP-50 Bulletin has placed great emphasis on the so-called *dust concentration method* of sampling. It is our experience that such method of field sampling introduces errors of such magnitude as to make the results wholly unreliable in the field of incinerator testing. Just by virtue of the variable nature of the incinerator fuel material, presently designed incinerators utilize methods of charging or feeding that cause serious disruption in the flow pattern through the unit. Even municipal incinerators which are unquestionably the best controlled in the matter of operation present varying and fluctuating flow patterns due to the opening and closing of charging and stoking doors, the flashy and variable nature of the feed material, the large temperature variations of the exhaust gases and the large and variable amount of excess air provided and used in the combustion process. To set a fixed sampling velocity at any particular sampling point in the duct on the basis of a single velocity determination performed an hour or two before the end of a dust test period, as is done in the *dust concentration method* of testing, ignores this fundamental consideration of the variable and fluctuating flow pattern characteristic of incinerator operation and performance. For this reason, we have chosen a *balanced static tube* sampling nozzle of our own design which is continually capable of following the variable flow patterns of an operating incinerator in obtaining a truly *isokinetic* sample of the flue gases and particulates associated with such sample. The balanced static tube works on the principle that when the velocity in the sampling nozzle equals the velocity in the duct at the sampling point, the static pressure as measured on the inside of the sampling nozzle will equal the static pressure in the duct at the sampling point. The sampling flow rate is continuously regulated during the entire sampling period to within a static balance of one hundredth (.01 in.) of oil to maintain this isokinetic sampling condition. Work done by Hemeon[1] and others have established that a balanced static tube method of sampling with conventional incinerator design velocities will give less than a 3% sampling error.

Dust testing or stack sampling of any kind involves the following basic considerations:

1. Securing an *isokinetic* sample from the duct or stack.
2. Filtration and measurement of the particulates contained in the sampled gases.
3. Measurement of the sampled gas volume.
4. Measurement of duct conditions as to temperature, pressure and composition of the effluent gases at the sampling point.

We have discussed the first consideration, that of representative sampling, in our analysis of the 2 test guides. However, the following specific suggestions apply to incineration sampling primarily. Because of the corrosive nature of incinerator gases (pH < 7.0), the relatively high moisture content of incinerator feed material, and the high temperatures of incinerator exhausts, several precautions must be taken in the sampling apparatus which are unnecessary in power plant testing. In the first place, the sampling probe must be made out of stainless steel, or something equally resistant to corrosion and high temperature conditions. In our tests of incinerators of all sizes, we have encountered stack

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[1] The Magnitude of Errors in Stack-Dust Sampling. W. C. L. Hemeon and G. F. Haines, Jr., *Air Repair* 4, 159-64 (Nov. 1954).

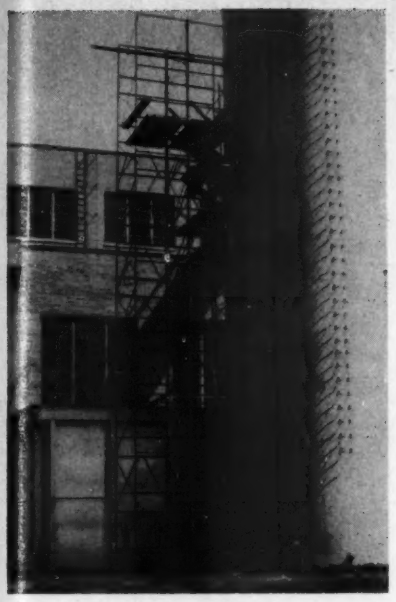

Fig. 1. Typical Municipal Incinerator Stack Test Platform.

or duct temperatures ranging from 700 to 1600°F. It is not unusual to have municipal incinerator gases run well above 1000°F. at the stack. For this reason we have water-jacketed our sampling nozzles. Water jacketing permits one to operate the filtration media within its temperature limitations, as well as to preserve the sampling nozzle itself. The water jacketing also permits the extension of the static pressure tubes outside the stack or duct within a circular cross-section which permits easy solving of the static seal problem at the sampling location.

Another sampling problem which is particularly acute in incinerator testing is to find a suitable sampling location. This is particularly true in municipal test work. Due to breeching design considerations, it is very often necessary to install or erect special test platforms to test at elevated stack locations. See Fig. 1 which illustrates a typical municipal incinerator stack sampling platform. Commercial or industrial incinerators seldom present such difficult and hazardous test conditions.

The ASME Test Code requires an overall filtration efficiency of the dusts in the sampled gases of 99.0% or higher. This presents some problems in the filtration of relatively large volumes of gases (15 to 27 cfm. at stack conditions) within the framework of a portable sampling and filtering device. After much experimentation, we have settled upon a modified sampler. This sampler contains a $1\frac{1}{2}$ in. diam. stainless steel cyclone and is followed by a bag collector housing where the high efficiency filtration of particulates is effected. The stainless steel cyclone is fitted to receive a standard Mason jar as a hopper. Thus the particulates are removed at 2 points in the filtration train—in a tared glass jar and in a tared bag filter unit. Herein presents a problem in incinerator testing, if strict technical compliance with the ASME Code is required. It is quite customary in incinerator testing to filter the largest weight portion of the total dust catch in the cyclone hopper jar, which incidentally also acts as an entrainment separator to preserve the bag filter units when wet flyash collection systems are evaluated. This leaves only a small weight of material to be caught in the bag collector unit. In order to insure a satisfactory margin of safety in filtration efficiency, and a minimum pressure build-up across the fabric filter, it is necessary to utilize approximately 1.0 to 1.5 ft.^{2} of filter surface in the bag unit. What with the temperature, filter efficiency, pressure drop and corrosive conditions involved, a bag which will meet these conditions and still fall into the suggested 5 to 1 *bag weight to catch* ratio does not now exist, unless one runs an unusually extended dust test run. This is particularly true in municipal incinerators where an effective, high efficiency wet scrubbing flyash removal system has reduced exit dustloadings to very low levels. Of primary importance, is to secure a highly stable fabric (weightwise) exhibiting the other required characteristics. With specialized laboratory techniques, we are confident that our work with a special cotton filtration fabric has introduced a minimum of error in this regard. We are engaged at present in a revaluation of the newest synthetic fabrics with an aim toward improving this condition, if possible. We are confident that our present test equipment is the best that we have examined for incinerator test purposes.

Measurement of the sampled gas volume is accomplished in a number of manners and is always double or triple checked on any field test job. These measurements involve calibrated pressure drop methods, Flowrator, and velocity determinations. Incinerator testing presents no unusual requirements in this regard not encountered in normal power plant testing. Our metering or volume measuring devices are all individually calibrated at regular intervals.

Conventional methods of temperature, pressure, and gas composition measurement are utilized in establishing duct or stack conditions. These measurements

Fig. 2. Some Field Test Equipment and Mobile Field Laboratory.

are similar to those encountered in any dust test work. However, special attention must be given to the wide fluctuations in gas temperature and composition. It is not unusual to have 200°F. variations in gas temperature in a matter of minutes. It is true, also, that gas composition varies over wide limits and fluctuates rapidly. Carbon-dioxide readings, for example, can vary from 1.0 to 12.0% with 2 or 3% variations in carbon dioxide content possible within minutes. It has, therefore, been desirable from a test standpoint to utilize portable continuous analyzing and indicating equipment. Measurement readings must be made frequently enough to be able to establish the average conditions over the entire test period. It is not felt that the need for continuous recording equipment justifies the additional expense involved. Furthermore, this equipment is not prone to portability and also presents some difficult handling and usage problems on crowded, element exposed test platforms. This equipment also makes for additional test personnel requirements if used at remote locations. See Fig. 2 which illustrates some of the test equipment used.

Much discussion in the past has centered around the calculations involved in correcting an exit dustloading to a 12% carbon dioxide or a 50% excess air basis. We all are cognizant as to why such correction or adjustment is necessary. Without having some standard basis of reporting dustloadings, there could be no common basis for comparison of results. Limitations would then be meaningless and quantitative control of particulate emissions would be extremely difficult, if at all possible.

The correction of an incinerator dustloading to a 12% CO_2 basis is virtually a linear function dependent on the average carbon dioxide content of the flue gases during the sampling period. Correction of an actual incinerator dustloading to a 50% excess air basis requires certain specific information and some assumptions to be made. In the first place, the moisture content of the feed material must be determined. With the widely

TABLE I
Final Dustloading Tests Summary
at City of Milwaukee Green Bay Avenue Incinerator

Test Run No.	Dustloading Determinations														
	Actual Loadings Encountered												Corrected to a 50% Excess Air Basis		
		Conditions		At Sampling Condition		At SCTP[a]	Sampling Conditions						At SCTP[a]	At Sampling Cond.	
	Date	Draft	Dust Collection	Grains/ft.³	Lb. Dust/ 1000 lb. Flue Gas	Gr./ft.³	Temp. °F.	Press. in Hg.	Orsat Analysis % CO_2	% O_2	% CO	% N	Gr./ft.³	Gr./ft.³	Lb. Dust /1000 lb. Flue Gas
1	4-20-54	Forced	Water Scrubber with Baffle	.0669	.370	.209	1100	29.45	6.75	13.60	0.10	79.55	.349	.1118	.621
2	4-21-54	Forced	Water Scrubber with Baffle	.0755	.434	.2385	1133	29.17	6.63	13.47	0.10	79.80	.405	.1282	.736
3	4-22-54	Natural	Water Scrubber with Baffle	.0514	.279	.159	1050	29.40	6.13	14.20	0.10	79.47	.290	.0940	.510
4	4-23-54	Natural	Water Scrubber with Baffle	.0631	.351	.206	1100	29.50	6.53	13.77	0.20	79.50	.353	.1083	.603
5	4-27-54	Forced	None	.1660	1.120	.598	1375	28.89	6.70	13.43	0.17	79.70	.993	.2756	1.860
6	4-28-54	Forced	None	.1123	.740	.403	1350	29.17	6.60	13.50	0.10	79.80	.690	.1922	1.265

[a] 32° F., 29.92 in. Hg.

varying nature of the feed material, this presents no little laboratory problem. Then, too, an ultimate analysis of the incinerator refuse material would be required in order to determine the theoretical air requirements of the feed material. An ultimate analysis of fuel of such widely varying consistency and content presents an almost impossible sampling and analytical problem. However, when one considers the type of material being charged to an incinerator — domestic, commercial and municipal, it has been determined that incinerator feed material reacts stoichiometrically as cellulose ($C^6H^{10}O^5$)[2]. Such assumption permits one to determine the theoretical air requirements and to calculate the weight of discharge gases at a 50% excess air condition on a usable basis. Average Orsat analyses data of the actually encountered stack gases permits one to calculate the actual weight of gases per pound of refuse fired. These 2 factors permit one to adjust the actual dustloading to a 50% excess air basis. It has been checked on numerous occasions that an incinerator dustloading corrected to a 12% CO_2 basis will vary only slightly from the same actual dustloading corrected to a 50% excess air basis. Such variation in the reporting of dustloadings is usually much less than 10%. A linear 12% CO_2 corrected or adjusted dustloading usually gives the higher dustloading figure of the 2 methods of calculation.

Incinerator Test Results

Time and space do not permit us to report on the hundreds of dust tests run so far, but the following general conclusions can be drawn from the incinerator test program to date. Table I illustrates a typical summary dustloading test results sheet for a municipal incinerator.

Domestic Incinerators

(Portable, below 5 ft.³ capacity)

This particular class of incinerators has received the least attention in our dust testing program to date. This was necessitated by time considerations only, and is not meant to reflect the relative contribution to our air pollution problem that this type unit produces. We have at present a very well organized test program underway with respect to this type incinerator unit. We are hopeful this program will establish some definite design recommendations which will reduce the particulate emission of this type unit. To this end, we have encouraged portable incinerator manufacturers servicing our area to include in their units many of those features that we have found to be effective in the commercial sized units — these include increased retention time by baffling, secondary settling chamber and draft control where possible. One is extremely limited in design considerations in this class of equipment due to physical size limitations. An evaluation of these modifications in pilot model incinerator units is currently underway. This class or size of incinerator unit has the odor problem as one of its major sources of complaints. While we have just begun to evaluate particulate emissions in this class of equipment, we have in the past conducted a thorough testing of virtually all the models of domestic units sold in our area for minimum draft requirements, visual smoke emission, burning tests, odor emission and physical factors. In this test work, we have yet to find a domestic incinerator capable of burning refuse containing as little as 10% garbage material that can consume the same without emitting a very disagreeable and offensive odor. It was our experience that when even such small percentages of wet material as 10 to 15% were included in the charge that maximum incinerator temperatures dropped from 1450°F. to well below 1000°F. This lack of combustion temperature plus a very, very limited

[2] Municipal Incineration. Sanitary Engineering Research Project, Univ. of Calif., Tech. Bull. No. 6 (November, 1951).

retention or detention time for the volatized gases, will probably preclude the possibility of ever achieving odor-free operation of this type unit where any wet material (garbage) is involved. The small heat input of the customary gas or electric auxiliary burner has little effect on the temperature of an operating unit. The so-called dehydration process effected by an auxiliary burner fails to reduce moisture content appreciably and more often results in offensive odor emission during the dehydration period.

Commercial and Industrial Size Incinerators

This particular class of incinerators has received an increasing amount of quantitative evaluation of particulate emission. It is in this class of equipment where we have spent the greatest amount of time on design considerations. Quantitative evaluation of results of these design factors in this class of equipment trails the developments and design experimentation. Our quite extensive tests to date permits us to report the following results:

1. That adjusted or corrected exit dustloadings increase as the burning rate decreases. This increase in adjusted exit dustloading at reduced capacity operation has been consistently noted. A 50 to 60% increase in corrected exit dustloading can be expected with a 40% reduction of burning rate in the absence of draft regulation.

2. That all other things being constant, that incinerator particulates increase with increased overfire draft. Each incinerator design has an optimum overfire draft setting which will permit capacity operation on each class of fuel. Operation of the incinerator above this optimum value will increase exit dustloadings from the unit. Likewise, operation of an incinerator at some capacity below the rated capacity without subsequent draft regulation will result in increased discharge or carryover of flyash. Corrected or adjusted dustloadings for this latter condition have been found to exceed the ASME permissible limitation for certain design incinerators. Dustloadings in the order of 1.0 to 1.1 lb. dust/1000 lb. flue gas, adjusted to a 50% excess air basis have been noted under these test conditions.

3. Substantial test data exists to show that for certain designs that exit dustloadings increase as much as 60% when the major portion of the combustion air supply is furnished through the grates as opposed to an overfire surface air supply. Exit dustloadings in this manner of operation have exceeded the permissible ASME limitation, ranging to 1.0 lb. dust/1000 lb. flue gas, adjusted to a 50% excess air basis.

4. That commercial and industrial incinerators that incorporate in their design the following fundamental features can operate below the ASME dustloading limitations:

a. Primary and secondary chamber
b. Increased retention time accomplished by drop curtain or baffle construction.
c. Reduced secondary chamber velocities
d. Built-in and auxiliary draft regulation
e. Proportioning of the unit to regulate capacity, flow and temperature conditions. These factors will be discussed in more detail under the design phases of this paper.

Exit dustloadings for incinerators incorporating these features vary for individual designs and the methods used to incorporate these features. We have tested units incorporating all, or a number of these features, and found exit dustloadings on the burning of Class I fuel ranging from 0.12 to 0.60 lb. dust/1000 lb. flue gas, adjusted to a 50% excess air basis. A detailed and elaborate testing program, probably financially feasible for only a large incinerator manufacturer or by an association of a number of incinerator manufacturers will be required to quantitatively evaluate the individual effect of each of the above fundamental factors.

5. That sufficient quantitative evidence exists to show that exit dustloadings decrease with an increase in moisture content of the fuel charged. A 50%-50% wet and dry mixture will give exit dustloadings in the order of 40% less than the same unit fired with an all dry (Class I) material under identical conditions.

6. That present tests indicate that the commercial sized incinerator units do not provide sufficient high temperature retention time to burn out all odors from the effluent gases when burning a fuel containing as little as 20% by weight of wet, garbage type material. Increase of temperature alone by auxiliary methods to the temperature limitations of normal refractories have failed to eliminate the odor discharges in this size unit.

Municipal Incinerators

By far the greatest test activity has been in the municipal incinerator field. The following general statements are based on our test results to date.

1. All municipal incinerators tested to date have been found to exceed the ASME limitation on dust emission when operated without the benefit of special dust and flyash collection equipment. Exit dustloadings of municipal incinerators tested to date, when operated with forced draft air, at rated capacity and without the benefit of flyash collection systems, range from 1.30 to 3.00 lb. dust/1000 lb. of flue gases, adjusted to a 12% CO_2 basis. Most of the test results are in the order of 2.00 to 2.70 lb. dust/1000 lb. flue gases, adjusted to a 12% CO_2 basis. Actual exit dustloadings for these conditions ranged from 0.25 to 1.20 gr./scf. (32° F., 29.92 in. Hg.). Stated in another manner, our tests indicated that particulates are emitted from a municipal incinerator in the range of 10.0 to 26.0 lb. dust/ton of charge. The bulk of the tests indicated that a discharge in the order of 20.0 lb. of dust/ton of charge is emitted from the stack from an incinerator operating without special flyash collecting equipment.

2. Sufficient data exists to definitely show increased exit dustloadings in municipal incinerators when a forced draft primary air supply system is used opposed to a natural draft primary air supply. Increases in exit dustloadings up to 100% with a forced draft system have been noted. The average increase of exit dustloadings in the same incinerator, all other factors being constant, with forced draft primary air being supplied as opposed to a natural draft primary air supply is 25 to 50%. All municipal incinerator manufacturers have found a forced draft primary air supply is needed to realize the high grate burning rates required in municipal burning practices (55 to 85 lb./ft.^{2} of grate/hr.).

3. Exit flue gas dustloadings vary directly with the rate of operation of the incinerator. The greater the burning rate/ft.^{2} of grate surface, the greater the exit dustloading. Insufficient data is available to more fully evaluate this relationship. Reduced rates of operation (75% of rated capacity) of municipal incinerators have shown as much as 30% reduction in exit dustloadings from those at rated operation.

4. It was felt early in our approach to the municipal incinerator particulate problem in Milwaukee County that it may be necessary to resort to a dust collection system exhibiting the efficiencies associated with electrostatic precipitation to stay within our air pollution limitations. With this in mind, one of the country's first high efficiency wet flyash control systems was designed and installed in the breeching of the Milwaukee Green Bay Avenue Plant. It was felt that this wet system, if it did not in

itself reduce emissions to a tolerable level, would act to cool the discharge gases to where a higher efficiency collection system might be utilized. Tests of the wet scrubber flyash control system installed at this plant indicated an approximate overall flyash collection efficiency of 60.0%. This was sufficient to reduce exit flue gas dustloadings to an average of 0.658 lb. dust/1000 lb. flue gas, adjusted to a 50% excess air basis, which is below the permissible limitation. Improvements in design and additions made to the fly-ash control system since the earlier tests undoubtedly have increased the efficiency of collection. Tests of improved design low-draft-loss, wet flyash collection systems of the same general type as originally installed in the Milwaukee incinerator that have subsequently been installed, have indicated over all collection efficiencies in the order of 85%. These high collection efficiencies on incinerator effluents realized by a well-designed wet scrubber flyash control system has made compliance with the strictest air pollution ordinance possible. The high investment cost of electrostatic precipitation is obviated on this particular application by the fine performance of a well designed wet scrubbing system. The wet collection system acts also as an absorbing system for the organic acids contained in incinerator exhausts. Also the wet collection system is beneficial in acting as a condensing medium for vaporized metallic fumes and gaseous hydrocarbons. We hope to initiate tests during this coming year to quantitatively evaluate these latter factors.

5. It has been definitely established by our tests to date that it is highly improbable that the ASME recommended dustloading limitation can be met by the incorporation of such dry flyash collection devices as checkerwork and refractory drop curtains, low velocity sedimentation chambers or combinations thereof. Six checkerwork patterns together with 6 drop curtains, or baffles, in an extended sedimentation chamber failed to reduce exit dustloadings to below the permissible ASME limitations in 1 municipal incinerator plant tested. Different combinations of these baffles and checkerwork patterns in the breeching of this municipal incinerator plant gave exit dustloadings that averaged from 1.20 to 1.40 lb. dust/1000 lb. flue gas, adjusted to a 50% excess air basis. Individual tests ranged to double these values. This plant has subsequently been modified to include a wet flyash scrubbing system that yields an average exit dustloading of 0.692 lb. dust/1000 lb. flue gas, adjusted to a 50% excess air basis.

6. Many volumetric tests of municipal incinerators have shown that approximately 12.0 to 16.0 lb. gas/lb. refuse is the customarily experienced stack gas ratio.

A Study of a Multiple Venturi Wet Collector*†

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An experimental model of a new type wet collector was investigated in the Harvard University Air Cleaning Laboratory at the request of the Division of Engineering of the U. S. Atomic Energy Commission.

This unit consists of single or multiple collection stages, each containing a Venturi tube and 2 spray generators. The principal collecting mechanism is the impingement of dust particles and water droplets in the spray chamber and in the Venturi tube where the saturated gas stream reaches a maximum velocity of 12000 fpm. This unit is not directly comparable to the Venturi scrubber since, in the latter device, water is atomized by the main gas stream at the Venturi throat, whereas in the experimental collector water sprays are introduced in plenums prior to and following the Venturis. Furthermore, the pressure drop in a Venturi scrubber ranges from 20 to 40 in. of water (due to energy requirements of atomization) as compared to 12 in. of water for the 4 stage unit. The rapid expansion of the saturated gas stream taking place in the Venturi throat is stated by the manufacturer to produce cooling (adiabatic expansion), which results in condensation on the dust particles. This effective increase in particle size then allows the particles to be more readily removed.

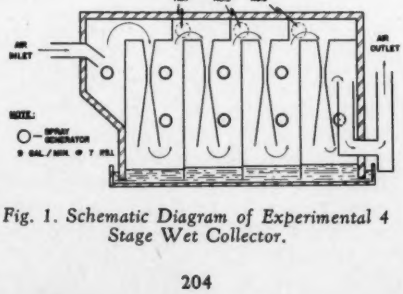

Fig. 1. Schematic Diagram of Experimental 4 Stage Wet Collector.

A special feature of this collector is the spray generating device which uses mechanical means rather than air or water pressure to produce a fine water spray.

This report describes results of tests with representative aerosols under a variety of operating conditions. Dust concentrations varied from 2 gr./1000 ft.^{3} to 2 gr./ft.^{3} and water rates from 6 to 12 gal./min./spray generator. Several combinations of spray generators were employed during multi-stage operation.

Description and Operation

Description

The experimental washer consists of 4 similar collection stages in series, each stage containing one Venturi tube and 2 spray generators as shown in Fig. 1 and 4. Oversized spray generators were installed in the test unit since the manufacturer could not obtain smaller spray generators. Therefore, water rates were stated to be higher for the 4 stage collector (120 gal./1000 cfm.) with respect to

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† This study was made under Contract No. AT (30-1)841 between the U. S. Atomic Energy Commission and Harvard University. Opinions expressed are those of the authors and do not necessarily represent the views of the U. S. Atomic Energy Commission.

Fig. 2. Large Size Spray Generator.

air handling capacities than those normally employed with similar commercial units (5 and 30 gal./1000 cfm. for 1 and 3 stage units, respectively). The spray generator consists of a fixed, circular manifold (11 in. diam.) having 8, relatively large orifices (3/16 in. diam.) equally spaced on the periphery. When water is supplied, the resulting jets are intercepted continuously by 16 bevelled vanes extending from a rapidly-rotating disc (3300 rpm.) located directly in front of the manifold. The spray generator in the test unit has a rated water capacity of 9 gpm. at 7 psi and requires a 1½ horsepower motor to energize the spinning disc, Fig. 2 and 3. The advantage of this type spray generator in comparison with conventional hydraulic or pneumatic spray nozzles is stated to be its non-clogging feature. The use of large diam. orifices permits extensive recycling of spray water without requiring a special filtration system to remove suspended solids.

During laboratory testing, 2 devices were used to remove entrained water droplets. For 1 and 2 stage operation an enlarged circular chamber containing 6 layers of a coarse woven wire screen was attached to the collector outlet. For 3 stage operation, a vertical riser was attached to the collector outlet so that the gas made an abrupt 90° turn upon leaving the collector. This device removed the same amount of water as the screen.

Operation

In operation, dust laden gas enters the plenum chamber of the first stage where it encounters the first spray generator. Collisions between spray droplets and dust particles in this area, followed by inertial separation (prior to entering Venturi tube), afford some degree of dust removal. The aerosol then enters the first stage Venturi tube where additional collisions occur as the aerosol passes through the Venturi tube. Here, due to an increase in approach velocity between the relatively large water droplets and the small dust particles in the accelerating air stream, significant target efficiencies are obtained. The velocity of smaller particles remains essentially the same as the gas velocity so that they pass through a zone of relatively slow moving large

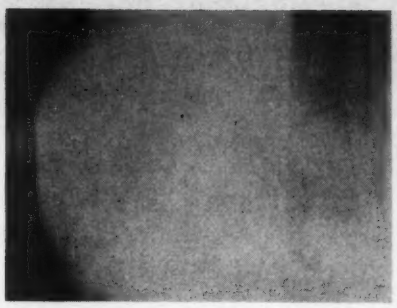

Fig. 3. Spray Generator in Operation.

particles which increases the probability of capture by impaction, *i.e.*, the target efficiency. Based upon an adiabatic expansion a temperature drop will occur during the expansion of the water saturated gas stream entering the Venturi throat. Calculations show the temperature change to be quite small. In addition, the short retention time during which dust particles can act as condensation nuclei, in the area of supersaturation, appears to eliminate this mechanism as an important factor in collection. After leaving the Venturi tube the aerosol enters a second plenum where it passes over the second spray generator. For single stage operation the aerosol is then withdrawn through a droplet eliminator. For multistage operation the cycle is repeated as shown in the schematic diagram, Fig. 1.

Test Methods

Aerosol Generation

Several test aerosols were employed in this study. Fly ash, calcium carbonate, talc and vaporized silica suspensions in concentrations greater than 0.2 gr./ft.^{3}, were produced by redispersing the dry dust with the Harvard generator.[1] In this device the dust is fed from a Syntron Vibrator onto a turntable (1 to 2 rpm.). An adjustable wiping arm removes the excess dust leaving a ribbon of any desired width along the periphery of the plate. A compressed air aspirator* operating at approximately 25 psi lifts the ribbon of dust from the turntable and ejects it into the inlet duct of the test system. For low dust loadings in the range of 20 gr./1000 ft.^{3}, the National Bureau of Standards dust generator was used. Here dust is fed by gravity from a small storage hopper to a slowly rotating spur gear. Dust is removed from between the gear teeth by an offset aspirating tube which ejects a steady flow of dust into the test air stream. A coarse sulfuric acid mist[2] was obtained by aspirating 2 normal sulfuric acid with compressed air at 90 psi and impinging it against a baffle located in an elutriation chamber to remove coarse droplets. A finer sulfuric acid mist [6] was formed by allowing drops of concentrated sulfuric acid to drop into a heated crucible, first producing sulfur trioxide which

Fig. 4. Experimental Wet Collector During Testing.

[1] M. W. First. et al. Performance Characteristics of Wet Collectors. AEC Contract No. AT (30-1)841, USAEC, NYO-1587 p. 23, Harvard Univ. (April 1953).

* ¾ in. water lifter with Venturi section.

[2] E. M. Berly. et al. Removal of Soluble Gases and Particulates from Air Streams. AEC Contract No. AT (30-1) 841, USAEC, NYO-1585, p. 19, Harvard Univ. (Oct. 1952).

[6] G. R. Gillespie and H. F. Johnstone. Particle Size Characteristics of Some Hygroscopic Aerosols, *Chem. Eng. Prog.*, p. 74-F, (1955).

[9] L. Silverman, M. W. First, G. S. Reichenbach, Jr. and P. Drinker. Final Progress Rept. AEC Contract No. AT (30-1)—GEN-238, USAEC NYO-1527, Harvard Univ. (Feb. 1950).

TABLE I
Size Parameters for Test Aerosols

Material	Median Diam. μ Count	Median Diam. μ Mass	Geometric Standard Deviation
Resuspended			
Fly Ash	0.6	14.3	2.7
Vaporized Silica[a]	0.4	0.6	1.5
Talc	1.3	2.5	1.6
Calcium Carbonate	0.6	2.6	2.0
Sulfuric Acid Mist—coarse	4.0	13.8	1.9
Copper Sulfate Microspheres	0.48	0.74	1.4
Iron Oxide Fume	0.03	0.6	2.0

[a] Size data refer to freshly generated amorphous vaporized silica.

rapidly formed a fine sulfuric acid mist. The copper sulfate aerosol[9] was generated by atomizing a 10% copper sulfate solution with compressed air (100 psi) through a pneumatic nozzle. Large droplets settle out in an elutriating chamber while the finer fraction passes through a pipe heated to 500-600°F. which produces anhydrous copper sulfate microspheres.

Iron oxide fume[10] was generated by burning undiluted iron pentacarbonyl in a high temperature air-butane flame. The iron pentacarbonyl is conveyed to the gas flame by entrainment in a nitrogen stream in order to eliminate fire and decomposition problems. Reference (10) contains an electron photomicrograph of the iron oxide particles produced by this method. This procedure for generating iron oxide is superior to the burning of iron powder since no metallic iron particles are injected into the gas stream. A limitation of this technique is that loadings above 20 gr./1000 ft.^{3} are difficult to obtain without introducing a potential fire and explosion hazard. Table I gives the size parameters for the dusts, fumes and mists used in this study.

Sampling Methods

Two separate sampling methods were employed to determine the dust concentration in the effluent gas stream. In the first method gross concentration was obtained by inserting into the effluent gas stream a sampling probe connected to a pleated filter,[3] paper thimble[3] or an impinger tube.[5] In the second method, the amount of dry or unwetted material in the collector effluent was determined by inserting a settling bottle in the downstream sampling line to remove coarse droplets (>10 μ) from the sampling line leading to one of the above collectors.

The weight collection efficiency of this unit has been determined with representative aerosols for several dust loadings, several water rates, and 1-2- and 3-stage operation. Some data have also been obtained on the percentage of wetted dust passing the droplet eliminator as compared to the total quantity of dust in the collector effluent. Pressure loss characteristics of the collector were also determined.

Results

The Effect of Dust Loading upon Weight Collection Efficiency

The effect of dust loading upon collection efficiency was observed for one stage operation with fly ash and calcium carbonate. Fly ash efficiencies (Table II) increased from 99.0 to 99.4% when inlet dust concentrations increased from 0.02 to 1.60 gr./ft.^{3} (an 80-fold increase in loading). However, in terms of penetration, the outlet fly ash concentration was reduced 40% (*i.e.*, 1.0 to 0.6% passage). With calcium carbonate, an increase in efficiency from 88.2 to 93.4% was observed for a 6-fold increase in dust loading (0.25 to 1.50 gr./ft.^{3}), which is equivalent to a 58% reduction in passage.

These data indicate that variations in inlet dust loading do not have an appreciable influence on collection efficiency for readily-captured aerosols such as fly ash. For finer aerosols, such as calcium carbonate, the increase in collection efficiency with dust loading becomes more significant. Increased retention with higher dust loadings is probably due to the greater opportunity for agglomeration as a result of higher particle concentration.

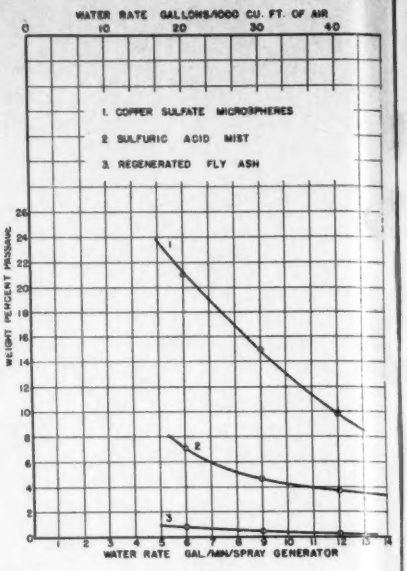

Fig. 5. Effect of Water Rate on Per-Cent Passage, 600 cfm. Air Flow.

The Effect of Water Rate Upon Penetration

The per cent passage for fly ash, copper sulfate microspheres, and coarse sulfuric acid mist at 6, 9 and 12 gpm./spray generator were obtained for single stage operation, Fig. 5 and Table IIa. All tests showed an inverse relationship between per cent passage and water rate within the range tested. The extent of the variation depended largely upon the per cent passage of the aerosol at rated water flow per spray generator, and was larger for the finer dusts. For the aerosols tested, doubling the water rate caused a reduction of approximately 50% in dust passage.

[9] See footnote 9, p. 205.

[10] C. E. Billings, W. D. Small and L. Silverman. Methods for Controlling Air Pollution from Steel Production Operation, Semi-Annual Rept. SA-3, Harvard Univ. (Oct. 1955).

[3] S. K. Friedlander. et al. Handbook on Air Cleaning, Particulate Removal, p. 54, U. S. Govt. Printing Office, Washington, D. C. (1952).

[5] P. Drinker and T. Hatch. Industrial Dust 2nd Ed., p. 147, McGraw-Hill Book Company, Inc., N. Y. (1954).

TABLE II [a]

Relationship between Inlet Dust Loading and Weight Collection Efficiency for One Stage Operation, a Water Rate of 9 gpm./Spray Generator and 600 cfm. at Room Temperature

Aerosol	Inlet Dust Loading gr./ft.^{3}	Weight Collection Efficiency %	Passage %
Fly Ash	0.02	99.0	1.0
	1.60	99.4	0.6
$CaCO_3$	0.25	88.2	11.8
	1.50	93.4	6.6

[a] Data presented in these tables are based on a minimum of three experimental runs.

TABLE II(a)

Relationship between Spray Generator Water Rate and Weight Collection Efficiency for One Stage Operation at 600 cfm. and Room Temperature

Aerosol	Water gal./1000 ft.^{3} of air	Inlet Dust Loading gr./ft.^{3}	Weight Collection Efficiency %	Passage %
Fly Ash	20	0.2	99.2	0.8
	30	0.2	99.4	0.6
	40	0.2	99.6	0.4
$CuSO_4$	20	0.6/1000	78.9	21.1
	30	0.6/1000	85.0	15.0
	40	0.6/1000	90.2	9.8
H_2SO_4	20	2.5/1000	92.8	7.2
	30	2.5/1000	95.5	4.5
	40	2.5/1000	96.2	3.8

The Effect of Air Velocity upon Collection Efficiency

The effect of air velocity upon collection efficiency was studied for one stage of the collector at rated water flow (9 gpm./spray generator) with copper sulfate microspheres. Test results showed an inverse relationship between air flow rates and collection efficiency, *i.e.*, 800, 600 and 400 cfm. air flow versus 82.8, 85.0 and 95.2% collection, respectively.

Since the velocity of the water droplets was in the order of 80 times that of the air stream in the plenum chamber (assuming that maximum droplet velocity was equal to the tangential velocity of the spray generator impeller), increasing the air velocity by a 2 or 3 fold factor had little effect on the relative (approach) velocity between the droplets (targets) and dust particles. It is believed that reducing the air flow did not enhance collection by diffusion mechanisms, since diffusion target efficiencies were calculated to be less than 0.3% for the estimated particle approach velocities.

The fact that efficiencies actually varied inversely with air velocity was attributed to a greater number of water droplets sweeping a given volume of air at the reduced air velocity which, in effect, increased the retention time of the dust particles in the spray system.

Dust Entrained in Water Droplets—Collector Effluent

By using the 2 procedures for effluent sampling described previously, it was possible to estimate the quantity of wetted dust (dust entrained in water droplets) in the effluent gas stream. The amount of dust contained by the water droplets may make a significant contribution (30 to 70%) to the total effluent loading at the sampling location, Table III. However, it is expected in commercial installation that only a very small amount of wetted dust particles (>10 μ) would be present in the stack effluent due to settling and inertial separation in the exit duct, fan and stack.

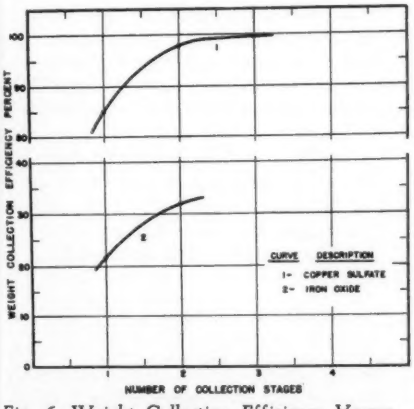

Fig. 6. Weight Collection Efficiency Versus Number of Collection Stages.

TABLE III

Effect of Sampling Method on Estimation of Effluent Loading (1 Stage Only) for a Water Rate of 9 gpm./Spray Generator and 600 cfm. of Air at Room Temperature

Aerosol	Inlet Loading gr./ft.^{3}	Outlet Loadings Dry gr./ft.^{3}	Outlet Loadings Wetted gr./ft.^{3}	Outlet Loadings Total gr./ft.^{3}	Efficiency Dry %	Efficiency Wet %
Fly Ash	0.15	0.0009	0.0015	0.0024	99.4	98.4
Talc	1.5	0.056	0.027	0.083	96.2	94.4
H_2SO_4 coarse	0.0025 mist[a]	0.00011	0.00027	0.00038	95.5	84.7

Dry refers to dust passing settling bottle in sampling line
Wet refers to dust entrained in water droplets retained in settling bottle

[a] No droplet eliminator in collector.

TABLE IV

Stage Collection Efficiency of Experimental Unit for a Water Rate of 9 gpm./Spray Generator and Air Flow of 600 cfm. at Room Temperature

No. Stages	1	2	3
Aerosol	percent	weight	collection
Fe_2O_3	20	32	—
$CuSO_4$	85	98	99.5+

Effect of Particle Size on Collection Efficiency

Sulfuric acid mist was generated by 2 methods: impaction of a 2 normal solution, against a baffle followed by elutriation, and decomposition of acid in heated crucible followed by water condensation on sulfur trioxide nuclei. The larger droplets (Mg. = 4.0 μ) generated by impaction were collected by one stage of the washer at an efficiency of 95.5%. The fine submicron mist formed by condensation was collected by one stage at an efficiency of less than 5%. This range in collection efficiency for large and small sulfuric acid droplets conforms to theory, which states that the target efficiency is a direct function of the particle diam.[2] (or free settling velocity). The free settling velocity of the larger sulfuric acid particles is approximately 70 times that of the submicron particle.

Multi-Stage Operation of Washer

Tests discussed so far have described only single stage operation of the experimental collector, that is one Venturi tube and 2 spray generators. Efficiency data for multi-stage operation with copper sulfate and iron oxide aerosols are reported in Table IV and Fig. 6. The results of these tests indicate that it is possible to estimate the increase in efficiency obtained by adding collection stages in series by the log-penetration law. Theoretically, the log-penetration law applies only to the collection of uniform aerosols (with respect to both size and composition) when 2 or more similar air cleaning devices are operated in series. Since neither copper sulfate nor iron oxide particles, as formed, were uniform in diameter, this relationship merely provides a convenient means for estimating multi-stage efficiency. In order for the second and third stage of the experimental collector to be as efficient as the first stage, the effluent from any preceding stage must have undergone sufficient conditioning (through agglomeration, particle and water contact, and possibly condensation) to approach the size distribution of the original aerosol. In the absence of particle conditioning, multi-stage operation would ordinarily be impractical.

Effect of Droplet Eliminators upon Over-all Collection Efficiency

Efficiency tests indicated that the screen droplet eliminator contributed little to total dust removal (0.7 and 2.0% collection efficiency for fly ash and coarse sulfuric acid mist, respectively) while removing approximately 1 gph. of water from the collector effluent. The vertical riser, used in 3 stage operation, removed (by inertial separation) about the same amount of water droplets (1 gph.) as the screen. When the second spray generator of the last collection stage (for single or multi-stage operation) was not operated, water droplet carry-over was considerably reduced.

Effect of Varying Number of Spray Generators on Collection Efficiency

A series of tests were undertaken to determine whether the collector could be operated with fewer spray generators (decreased water rate and power consumption) without causing an appreciable change in collection efficiency. Eliminating the downstream spray generator in single stage operation (Table V) (a 50% reduction in water rate) caused a decrease in collection efficiency

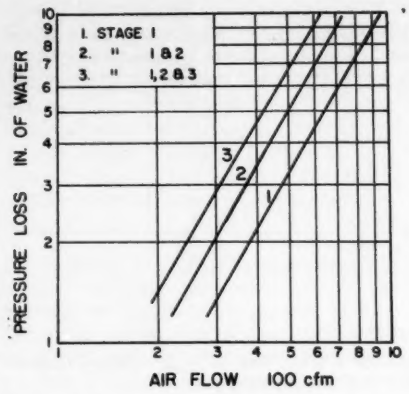

Fig. 7. Pressure Loss Characteristics of Experimental Wet Collector at Room Temperature.

of about 2%. However, passage increased by as much as 50%. With 2 stage operation (use of 2 Venturi tubes) removal of the fourth spray generator, located downstream of the second Venturi tube, decreased the water rate by 25% and caused no significant change in either collection efficiency or penetration (Table VI). When either the second (lower) or third (upper) spray generators were shut off, a significant reduction in collection was observed in comparison to normal 2 stage operation. Based upon a rated 2 spray generator/stage, water demand in these cases was reduced by 25%. Collection efficiencies were reduced from 32 to 20% for iron oxide fume and from 98 to 96% for copper sulfate microspheres. Results of these tests indicate that the concentration of water droplets is an important factor in multi-stage operation. This agrees with the theoretical relationship employed by Feild[17] between per cent passage and droplet concentration.

One spray generator between Venturi stages did not furnish sufficient droplets to bring about efficient contact with the small particles entering the second stage of the collector. Relatively high efficiencies for one stage operation were attributed to removal of the coarser fraction of the aerosol.

[17] R. B. Feild. Collection of Aerosol Particles by Atomized Sprays, AEC Contract No. AT (30-3) -28, Tech. Rept. No. 5, Engineering Experimental Sta., Univ. Illinois (1951).

TABLE V

Collection Efficiencies for 1 Stage Operation with Second Spray Generator On and Off, a Water Rate of 9 gpm./Spray Generator and an Air Flow Rate of 600 cfm. at Room Temperature

Aerosol	Weight Collection Efficiency %		Passage %		Inlet Loading gr./ft.^{3}
	2 spray generators	1 spray generator	2 spray generators	1 spray generator	
Fly Ash	99.4	98.7	0.6	1.3	1.65
$CaCO_3$[a]	93.4	91.2	6.6	8.8	1.5
Talc	96.2	94.4	3.8	5.6	1.5
H_2SO_4	95.5	94.0	4.5	6.0	2.5/1000

[a] Efficiencies given are based on gross (wetted and dry dust) effluent samples.

Sulfur Dioxide Removal

Sulfur dioxide was selected for investigating the collection efficiency of the experimental washer on gases which may accompany operations where iron fume and fly ash are created. For an inlet gas concentration of 180 mg./m.^{3} and with 3 stage operation a collection efficiency of 91.4% was obtained. Since high water rates frequently necessitate recycling, the accumulated acids in this collector (or any wet collector) may present a corrosion problem unless neutralization or precipitation practices are employed. As the percentage of sulfurous acid in the spray water increases, it is expected that the collection efficiency would be reduced.

The Effect of Air Velocity and Number of Stages on Pressure Loss

Pressure loss data for single and multiple stage operation of this collector are presented in Fig. 7. These values include the pressure loss through the vertical exit pipe employed as the droplet eliminator. At a rated flow of 600 cfm. a pressure loss of 4.5 in. water was measured for single stage operation. An increase in pressure loss ranging from 2 to 3 in. water/collection stage was found for multi-stage operation at 600 cfm. The pressure loss varied as the 1.75 power of the velocity for a fixed number of stages. Operation of the spray generators was found to produce no measurable effect upon the pressure loss.

List of Symbols—consistent units

D	Target (droplet) diameter of average volume.
D_P	Particle diameter
D_T	Target diameter.
N	Target concentration-number/unit volume.
N_o	Initial target concentration-number/unit volume.
Q	Air flow rate
t	Time.
V_a	Gas velocity.
V_T	Target velocity.
$\overline{V}$	Approach velocity.
w	Water rate.
$E_{Dp\,Dt}$	Fractional target efficiency for given size parameters.
η	Target efficiency
ρ_P	Particle density.
μ	Gas viscosity.
Δ	Target of average projected area.

Theoretical Discussions

In order to estimate the performance of any wet collector which depends upon intimate contact of water droplets and dust particles for air cleaning, the evaluation of individual droplet target efficiencies (for collection of dust particles of a specified diameter) is of primary importance. Although various functions have been suggested as a means of defining target efficiencies[12,16] the impaction parameter suggested by Langmuir and Blodgett has been employed in this study.

$$\text{Target efficiency} = \eta = f\,\frac{\rho_p \overline{V} D_p^{\,2}}{18\,\mu\,D_T} \qquad \text{(a)}$$

For a given system containing water droplets and dust particles, each of uniform size, the relative (approach) velocity between droplets (targets) and dust

TABLE VI

Weight Collection Efficiencies for Various Combinations of Spray Generators during Two Stage Operation of the Experimental Unit at 9 gpm./Spray Generator and an Air Flow of 600 cfm. at Room Temperature

Aerosol	Spray Generators Used[a]	Inlet Loading gr./1000 ft.^{3}	Weight Collection Efficiency %
Iron Oxide Fume	1,2	10	19.9
	1,3	14	20.6
	1,2,3	10	30.1
	1,2,3,4	15	31.6
Copper Sulfate Microspheres	1,2	0.4	86.8
	1,2,3	0.4	98.0
	1,2,3,4	0.4	98.0

[a] Number refers to a specific spray generator and indicates its location relative to direction of air flow.

particles determines the target efficiency. Therefore, to apply Equation (a) to the physical conditions existing in the experimental washer, the magnitude of approach velocities within the plenum chamber and Venturi tubes must be known. Spray droplets are presumed to leave the spray generators at velocities approaching the tangential velocity of the blades. Since the air velocity within the plenum chamber is low (about 2 fps), a high relative velocity between droplets and dust particles is maintained regardless of spray angle. Average target efficiencies within the plenum for water droplets ranging from 400 to 50μ in diam. vary from 30 to 42% with respect to 0.5 μ copper sulfate spheres. Although droplet Reynolds numbers ranging from 335 to 35 actually place the motion in the intermediate flow range, estimation of droplet projection velocities within the plenum were based upon turbulent flow conditions. This is in accordance with Dalla Valle's statement,[18] "*If the fluid is in turbulent motion, the motion of a particle injected into it will be turbulent regardless of the relative velocity between the particle and the fluid.*" A constant drag coefficient of 0.44 was assumed in calculating approach velocities.

The estimation of target efficiency in a Venturi tube is difficult due to the acceleration and deceleration of the air stream while passing through the Venturi tube. It is assumed that submicron dust particles will remain essentially at the same velocity as the accelerating air stream. The relatively large water droplets, due to their greater inertia, will lag the air stream in the converging section of the Venturi. The droplet velocity lag (or lead in the diverging section if the initial droplet velocity is sufficiently high) will result in a significant approach velocity and target efficiency. Experimental measurements are necessary to determine the absolute velocity of water droplets in accelerating gas streams in order to permit calculation of target efficiencies in a Venturi tube since the computation of drag forces becomes complex when gas stream turbulence also influences particle motion.

Once the target efficiency for an individual droplet is known, the total efficiency of a segment of the washer may be calculated in the following manner. The fraction collected for a system involving uniform diameter dust particles and water droplets is expressed by the following equation[17]

$$E_{Dp,Dt} = 1 - exp\left[- \int_o^t \eta N \frac{\pi}{4} D_T^2 \bar{V} dt \right] \quad (b)$$

The volume concentration of the water droplets increases in a converging gas stream since their inertia prevents them from attaining the gas stream velocity. Since the mass flow of water must be constant the spray droplet concentration at any distance along the Venturi relative to the initial value (No) must follow the relationship

$$N = N_o \left(\frac{V_a}{V_T} \right) \quad (c)$$

Substituting in Equation (b)

$$E_{Dp,Dt} = 1 - exp\left[- \int_o^t \eta N_o \left(\frac{V_a}{V_T} \right) \frac{\pi D_T^2}{4} \bar{V} dt \right] \quad (d)$$

The initial spray droplet concentration may be defined in terms of water rate (w) and gas glow rate (Q).

$$N_o = \frac{w}{\frac{\pi}{6} D_T^3 Q} \quad (e)$$

Substituting in Equation (d)

$$E_{Dp,Dt} = 1 - exp\left[- \frac{3}{2} \frac{w}{Q D_T} \int_o^t \eta \left(\frac{V_a}{V_T} \right) \bar{V} dt \right]$$

The integral portion of Equation (f) represents the effective length of travel, $\bar{s}$, of the water droplet through the gas stream in the plenum chamber or in the Venturi section.

Application of Equation (f) toward evaluating the efficiency of the Venturi generators near or immediately above section is feasible if droplet velocities can be determined at the Venturi inlet. The numerical value of $\bar{s}$ varies by only ±25% for droplet diameters ranging from 200-50 μ, provided that initial droplet velocities approximate that of the air stream. This is due to the inverse relationship of the terms defining $\bar{s}$ in Equation (f). For decreasing droplet diameters, η increases while $\bar{V}$ decreases. At the same time the droplet concentration is decreasing. Target efficiencies also do not increase appreciably for dust particles ranging from 0.5 to 1.5 μ in diam. (representing the major portion of fine dust).

It should be noted, however, that the droplet diam. defining average projected area (Δ) and that describing average volume (D) are identical only when the spray is uniform. The proper value for the term D_T in Equation (f) is the reciprocal of the surface area/unit vol. (Δ^2/D^3). This term may be calculated from the mean size by count or weight according to the Hatch-Choate Equation.[5]

Comparison of Experimental Washer with Several Wet Collectors

Collection efficiency data from a previous investigation of a mechanical centrifugal wet collector are available for several of the dusts employed in this study. The wet collector studied[7] was tested at 900 cfm. with a total water rate of 6.5 gpm. at 5 to 15 psi. A comparison of the collection efficiencies of this collector and the experimental collector is shown in Table VII for similar aerosols. Although the present unit has the higher collection efficiency, for one stage operation, the water consumption is considerably higher (4 times). Collection efficiency data for a cyclonic scrubber,[8] a venturi scrubber,[5] and a fog tower,[9] are also shown in Table VII. The cyclonic scrubber has a lower efficiency than the experimental washer for a coarser fly ash aerosol, but uses about one-third as much water. The cyclonic scrubber has a higher efficiency for sulfur dioxide which may be due, in part, to the use of a weak alkali spray liquid. The venturi scrubber has a much higher collection efficiency for a similarly sized iron oxide fume (99%) than the present unit (22%). It should be noted, however, that the test fume generated in this laboratory was 100% iron oxide in contrast to mixtures of iron oxide fume and mineral dusts encountered in field applications. Furthermore, since the concentration of the fume in the venturi scrubber was approximately 100 times that used in this study, agglomeration may partially account for better collection. The fog tower appears superior to the experimental unit in the collection of sulfur

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[12] C. J. Stairmand. Dust Collection by Impingement and Diffusion, *Trans. Inst., Chem. Eng.* (London) **28**, 30 (1950).

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[15] F. D. Ekman and H. F. Johnstone. *Ind. Eng. Chem.*, **43**, 1358 (1951).

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[18] J. M. Dalla Valle. Micromeritics. 2nd ed., p. 40, Pitman Publishing Corp. (1948).

[17] See Footnote 17, page 208.

[5] See Footnote 5, page 206.

[7] M. W. First. et al. Air Cleaning Studies, Progress Rept. AEC Contract No. AT (30-1) 841, USAEC, NYO-1586, Harvard Univ. (Feb. 1953).

[8] L. C. McCabe. Proc. U. S. Conf. on Air Pollution, McGraw-Hill Book Co., Inc., N. Y. (1942).

[9] See Footnote 9, page 205.

TABLE VII

Comparative Performance of Several Wet Collectors

Unit	Run No.	Aerosol	Loading gr./ft.$^{3(a)}$	Water Rate Gal/ 1000 ft.^{3}	Spray Liquid	Water Pressure psi	Collection Efficiency %
EXPERIMENTAL	1	Fly Ash	1.65	30	water	7	99.6
One Stage	2	$CaCO_3$	1.5	30	water	7	93.4
Operation	3	Talc	1.5	30	water	7	96.2
	4	Vaporized Silica	1.0	30	water	7	96.3
	5	Fe_2O_3	19/1000	30	water	7	21.8
	6	H_2SO_4 (mist-coarse)	2.5/1000	30	water	7	95.5
	7	H_2SO_4[b]		30	water	7	<5
	8	$CuSO_4$ (microspheres)	0.6/1000	30	water	7	85.0
	9	SO_2	180 mg./m.^{3}	90	water	7	91.4
Three stage Operation Mechanical Centrifugal Wet Collector		Fly Ash	1	6.5	water	5-15	98.4
		Talc	1	6.5	water	5-15	77.1
		Vaporized Silica	1	6.5	water	5-15	94.0
		$CuSO_4$ (microspheres)	1	6.5	water	5-15	81.1
CYCLONIC SCRUBBER		Fly Ash (2-5 + μ)	.5-2.6	3-10	water		88-98.8
		SO_2	100-150 mg./m.^{3}		Water+ weak alkali		94.5-96.8
VENTURI SCRUBBER		Fe_2O_3 (.02-.50μ)	1-6		Caustic		99
		Humidified SO_3,	10.6 mg./m.^{3}	2-6	water		
		H_2SO_4 mist			water		99.4
FOG TOWER		SO_2	230 mg./m.^{3}	30[c]	Caustic	450	98.3
		Chamber process	150 ppm.	70	water	500	99
		SO_2, SO_3. H_2SO_4			water		

(a) Unless noted.
(b) Formed by evaporation and condensation of H_2SO_4—fine particle size.
(c) Stated to be lower for larger unit.

dioxide (98% compared to 91%). However, the use of caustic solution would account in part for the higher efficiency.

Power requirements for *one stage* operation of the experimental washer are estimated to be 0.1 hp. for water delivery, 0.5 hp. for air flow (600 cfm.) and 3 hp. for spray generator operation, a total of 3.6 hp. In comparison, a 600 cfm. Venturi scrubber operating at a pressure loss of 20 in. of water is estimated to require 2.0 hp. *Three* stage operation with the present unit utilizing 5 spray generators, requires approximately 8.5 hp. However, a 3 stage commercial unit is reported to operate at 4.0 hp.

It is difficult to compare directly many types of wet collectors since available performance data are often based upon a variety of aerosols and different inlet loadings, air flow rates and water flow rates. For these reasons comparisons among different units should not be interpreted too rigidly.

Collection Efficiency with High Pressure Hydraulic Spray Nozzles in Converging Cone of Venturi Tube

It appeared that a large fraction of the water spray was removed in the plenum chamber by settling and impaction against the plenum walls according to measurements of the volume of water removed by the eliminator section. This factor suggested that location of spray generators near or immediately above the inlet to the Venturi tubes would provide better collection due to the presence of more droplets in the Venturi section. In fact, this principle has been employed in a foreign commercial version of the experimental collector and also in the Aerojet Venturi Washer[11] for which 98.3% efficiency for carbon black has been reported. The latter unit uses a concurrently-directed, pneumatic *atomizer* in the Venturi inlet, and requires 0.6 gpm. and approximately 2.9 hp./1000 cfm. of air.

Because the spray generators were too large to locate within or above the Venturi tubes, several types of small high pressure spray nozzles were substituted and placed immediately within the Venturi entry. During this section of the study the standard spray generators were not used. Substitution of hydraulic sprays in the entry to the Venturi tube of the unit which simulated the basic design of the Aerojet Venturi Washer afforded preliminary evaluation of this scrubber and also a comparison of several types of hydraulic nozzles.

Table VIII furnishes the manufacturers ratings and a brief description of the various nozzles tested in the Venturi section of the experimental collector. Type, number and orientation of spray nozzles, total water delivery, water pressure and collection efficiency for the copper sulfate aerosol described previously are shown in Table IX. Air flow was held constant at 600 cfm., corresponding to a 12000 fpm. Venturi throat velocity. The pressure drop was found to be practically independent of nozzle operation for concurrent sprays. In all concurrent spray tests the spray nozzles discharged 1 to 2 in. below the entry to the Venturi section. During the counter-

TABLE VIII

Description of Commercial Nozzles Tested in Modified Collector

Code No.	Delivery at 100 psi gpm.	Description of Operation
AA6FC	2.3	Spray formed by shearing of continuous spiral sheet from single jet
B12FC	9.5	"
P120	3.8	Impingement upon pin of single jet from nozzle.
J. B. No. 2-½ Hard Center	0.31	Whirling fluid passes through orifice in disc to produce fine spray

[11] R. M. Boucher. *The Industrial Chemist* (Feb. 1953).

current spray test the nozzles discharged 8 in. below the entry to the Venturi.

Nozzle operation data described in Table IX show that collection efficiency generally varied directly with water rate (hydrostatic pressure) for a given nozzle. This is attributed to 2 factors. There is an increase in water droplet concentration due to a higher water flow and for the same water volume more droplets are obtained due to a reduction in droplet size of the spray. It should be noted that the J. B. nozzle showed a higher collection efficiency at the lower pressure and water rate (39.8% at 100 psi.) than at the higher pressure and water rate (21.6% at 400 psi). These data are not inconsistent with theory, however, since Johnstone[19] and Stairmand[12] point out that there exists a lower limit in spray droplet size below which individual spray droplet impaction efficiency decreases. Although the impaction efficiency varies inversely with the target diameter, it also varies directly with the approach velocity of the particle to be collected. Since droplets < 100 μ in diam. have small free settling velocities, the approach velocity between dust particles and water droplets becomes very small, thus reducing target efficiencies[12].

The manufacturers' specifications describe the J. B. nozzle as a *fog-type* which, in terms of the largest particles present in a natural sea fog, indicates a 40 μ size range. The fact that the J. B. nozzle showed reduced efficiency at high pressure was attributed to a significant decrease in spray droplet size which decreased the target efficiency. Simultaneously, a variation in spray pattern with pressure may cause a larger fraction of the droplets to impinge upon the walls of the Venturi or to be swept aside, thus reducing the effective number of droplets in the gas stream.

On the basis of data obtained with several types of hydraulic nozzles, it appeared that introducing water sprays in the Venturi inlet resulted in higher collection for this section of the experimental washer. For example, in using the downstream spray generator alone with single stage operation, the copper sulfate efficiency was 64%. In this case the Venturi tube saw no water. Furthermore, operation as a dry settling chamber (no water sprays) showed 10 to 21% copper sulfate removal. With the upstream spray alone, collection efficiency averaged 75%. Therefore, as a rough approximation, the Venturi tube removed about 15% of the entering dust loading when 9 gpm. of water was delivered to the upstream plenum.

On the other hand Table IX shows that efficiencies in the order of 50% are obtainable at lower water rates with the spray device at the Venturi inlet. This figure takes into account that about 10 to 15% of the total dust load will be separated inertially prior to entering the Venturi. Significant collection in the downstream plenum appears unlikely since entrained water droplets in this section no longer have high velocities relative to the main airstream.

The data of Table IX do not necessarily represent optimum performance for any one nozzle arrangement. However, they do indicate that the effectiveness of Venturi sections are a direct function of the water droplet concentration, (with the exception of the J. B. nozzle). A direct comparison of nozzles is not justified since the cone angle determines the volume of water that will impinge upon tube walls and be removed from the airstream. Future studies in this laboratory will be directed toward use of the spray generator or nozzles located at the entry to Venturi section.

TABLE IX

Collection Efficiency for Copper Sulfate with High Pressure Hydraulic Spray

(Nozzles Located Within Venturi Tubes at 600 cfm.)

Run No.	Nozzle Type (see Table VIII)	Orientation	Water Pressure psi	Power Required for Pumps H.P.	Total Water Delivery gpm.	Collection Efficiency %
1	AA6FC	Concurrent	100	0.128	2.2	33.3
7	AA6FC	"	400	1.07	4.6	68.7
3	P120	"	100	0.227	3.9	56.4
6	P120	"	300	1.152	6.6	65.8
4	J.B.2-½	"	100	0.019	0.32	39.8
8	3 J.B.2-½	"	400	0.453	1.95	65.9
5	J.B.2-½	"	400	0.151	0.65	21.6
2	B12FC	"	75	0.345	7.9	55.0
9	2 AA6FC	Countercurrent	300	1.40	8.0	72.2

Conclusions

1. Collection efficiency is not markedly increased by high inlet concentrations for coarse, and usually readily-captured particulates such as fly ash. Finer dusts, calcium carbonate, show a distinct improvement in collection at high loadings due to the effective increase in particle diameter brought about by agglomerate formations. Collector ratings upon a basis of per cent penetration show a slight decrease for fly ash and a significant reduction (58%) in effluent concentration for calcium carbonate.

2. Increased water rates cause a significant decrease in penetration (increase in efficiency). For the aerosols studied, a doubling of the water rate produced a 50% decrease in penetration.

3. Collection efficiency varies inversely with air flow rate for fine particulates indicating that collision of water droplets and dust particles is the primary collecting mechanism. A 15% increase in efficiency (82.8 to 95.2%) was noted for a 50% decrease in air flow (800 to 400 cfm.), with copper sulfate.

4. The relationship between efficiency and number of collection stages is approximated empirically by the log-penetration law.

5. Operation of the final spray generator with multi-stage operation does not appear practical since no significant gain in collection efficiency was noted. Removal of the final spray generator caused a large reduction in water carry-over.

6. Water volume and power requirements for spray generation apparatus are higher for the experimental washer than those for many common wet collectors without appearing to offer a proportionate increase in collection efficiency. However, the non-clogging characteristics of the spray generators may eliminate the need for elaborate filtering apparatus and thus permit the economic recycling of the spent spray water in regions of sparse water supply.

7. Separate evaluation of the Venturi tube with spray nozzles located in the inlet show that collection efficiency in this section is increased significantly, although total water rates are much lower than employed with spray generator operation. During normal operation of the unit, most of the dust is removed in the spray plenums. This is due to a water droplet deficiency in the Venturi tubes.

[12] See Footnote 12, page 208.

[19] H. F. Johnstone, M. N. Roberts, *Ind. and Eng. Chem.*, 41, 2417 (1949).

A Study of A Multiple Venturi Wet Collector

Written Discussion

E. L. Krieble
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Harrisburg, Pa.

Mr. Chairman, in the first place I would like to congratulate the authors on the excellent manner in which this work was performed and also on a very comprehensive and well executed report on this new type dust collector.

There are certain comments I would like to make pertaining to the report which may assist in the understanding of this principle of gas washing.

The authors, in developing their theory, assume that the water droplets leave the spray generator at approximately the tangential velocity of the blade. If this is the case and the spray is thrown off the periphery of the blade wheel, the water spray would leave at a greater angle than actually is found. Rather, the spray is generated by impaction with the blades and leaves the generator in a more forward direction, shortly thereafter being airborne at essentially the velocity of the gas stream. I have a photo here showing the spray produced by a single jet of a spray generator to show this forward motion of the spray at what we consider a much lower velocity than the tip speed of the blade. (Fig. 1).

The authors state that the temperature drop in the venturi throat is quite small and that the short retention time in this zone appears to eliminate condensation of water on the dust particles as an important factor in collection.

It is true, we have calculations to show that this temperature drop amounts to only 0.81°F. However, we also calculate on the same basis that this drop is sufficient to condense 0.0136 gm. of water/ft.³ of saturated gas on the dust particle surfaces which act as condensation nuclei.

If this quantity of water is distributed on the surface of equal sized 1 μ diam. spherical particles, it will give the following thickness of water film on each particle, assuming a particle specific gravity of 1.2. At a loading of 0.02 gr./ft.³ 0.7 μ water film. At a loading of 2 gr./ft.³ 0.022 μ water film. Other particle sizes will have film thicknesses in proportion to the particle diam.

The transformation of dry dust particles into droplets of water containing the dust may be obtained by mere condensation on their surface if there is a large expansion and a sufficiently long time. A similar result can be obtained in a much shorter time in a 2-phase process:

First, by condensing a very thin layer of water on the particle surface;

Second, agglomeration between a droplet of mist in the gas stream and this particle of dust with a thin layer of water on its surface.

We believe that these two phases take place in succession in the venturi section; the first phase in the throat, the second phase in the expansion section. If condensation does not occur, the agglomeration between dry dust and water mist is quite low.

We note 2 abnormally low efficiencies in the results; namely, the runs on iron oxide and fine sulphuric acid fumes.

It is the considered opinion of our associates having the experience of some thirty diversified commercial applications of this principle that the condensation effect is cancelled if the particle is subjected to some heat emission bringing its surface temperature to a value higher than that of the saturation temperature of the gas. This can happen in the case of pyrophoric dusts or mists. In the iron oxide production for the creation of artificial fume, some elemental iron may enter the venturi and oxidize, releasing heat which will prevent condensation of water on its surface. The same condition can result with particles of concentrated sulphuric acid or sulphur trioxide fumes. The increasing temperature of the particle is all the more important as the particle becomes smaller since the ratio of the mass to the condensation surface is proportional to the diameter. This effect, negligible with 4 μ diam. particles, becomes 8 times more important with 0.5 μ diam. particles and may thoroughly prevent any condensation.

Another factor in the tests on iron oxide is the particle size itself. The present industrial applications are concerned with particles larger than the finest particles used in these tests. As an example: 3 stages of washing on blast furnace gas with a mean diam. of 0.1 μ by count and a mean diam. of 2 μ by mass and a standard deviation of 4 resulted in a 99.9% weight efficiency removal. This does not mean that finer particles cannot be removed; however, certain modifications would be required.

I have a set of calculations pertaining to this discussion on temperature drop and condensation which are too lengthy to go into at this time. However, I wish to present them to the Chairman of this meeting as a part of this written discussion.

For a Reversible Adiabatic Process:

$$\frac{P_1}{P_2} = \left(\frac{T_1}{T_2}\right)^{\frac{k}{k-1}} \tag{1}$$

For flow through venturi the following equation will apply for compressible fluids:

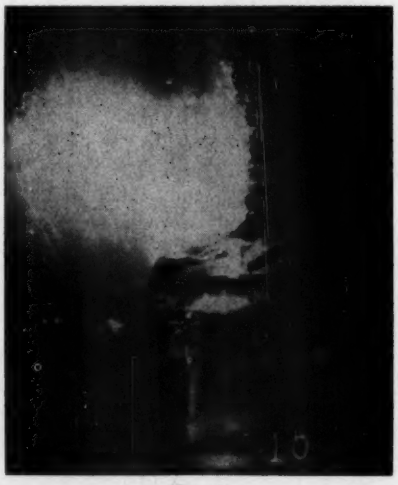

Fig. 1.

$$V_2^2 - V_1^2 = \frac{2\,C_1^2}{k-1}\left[1 - \left(\frac{P_2}{P_1}\right)^{\frac{k-1}{k}}\right] \tag{2}$$

Ref. Fluid Mechanics; Dodge & Thompson First Ed. p. 373. Substituting equation (1) in equation (2) the following results:

$$V_2^2 - V_1^2 = \frac{2\,C_1^2}{k-1}\left[1 - \frac{T_2}{T_1}\right]$$

or:

$$V_2^2 - V_1^2 = \frac{2\,C_1^2}{k-1}\left[\frac{T_1 - T_2}{T_1}\right]$$

Call $T_1 - T_2$, ΔT (3)

then:

$$V_2^2 - V_1^2 = \frac{2\,C_1^2\,\Delta T}{T_1\,(k-1)} \tag{4}$$

For small values of ΔT and with V_1 small in comparison to V_2 we will write equation (4) as

$$V_2^2 = \frac{2\,C_1^2\,\Delta T}{T_1\,(k-1)} \text{ where } \Delta T = T_1 - T_2$$

Assume $V_2 = 50$ *meters/sec. or 164 ft./sec.*
C_1 = Velocity of sound in air @ 68°F. = 1050 ft./sec.
$T_1 = 68 + 460 = 528$°R.
$k = \frac{C_p}{C_v} = 1.408$ *for air.* (5)

$$(164)^2 = \frac{2 \times (1050)^2\,(\Delta T)}{528\,(1.408-1)}$$

$\Delta T = 2.63$°R *or* °F *since* ΔT *is concerned.*

This shows a decrease in temperature of 2.63°F. in the fluid from a point upstream of the venturi to a point in the throat of the venturi.

This condition would exist if the fluid behaved as a perfect gas mixture with no condensation taking place. Such is not the case.

Let us now estimate the enthalpy difference for this difference in temperature with initially saturated air at 68°F. (no condensation).

Sat'd air contains 0.01471 lb. water vapor/lb. dry air.
C_p *for dry air* = 0.24 *Btu./lb./°F.*
C_p *for water vapor* = 0.44 *Btu./lb./°F.*
$2.63 \times [0.24 + 0.44\ (0.01471)] = 0.646$ *Btu./lb. dry air +* H_2O *vapor.*
At 68°F. 1 lb. dry air+water vapor to saturate it occupies 13.61 ft.³

$$\frac{0.646}{13.61} = 0.0475 \text{ Btu./ft.}^3 \text{ saturated air.}$$

As a matter of fact condensation does occur to follow the saturation curve.

Psychometric tables give approximately 0.8 Btu./lb. dry air difference in total heat for a change of 1°F. in the range of 68°F. for saturated air.

$$\frac{0.8}{13.61} = 0.0587\ \text{Btu./ft.}^3/\text{°F.}\Delta T.$$

Since above we have calculated available as total heat only 0.0475 Btu./ft.³ we may

estimate the actual temperature drop in the venturi to be the ratio of the heats available as calculated above or:

$$\Delta T \text{ (actual)} = \frac{0.0475}{0.0587} = 0.81°F.$$

Since the condensation condition was calculated for 1°F.

At 68°F. saturated air contains 103.0 grains H_2O/lb. dry air. At 66°F. saturated air contains 95.9 gr. H_2O/lb. dry air.

$$\frac{103.0 - 95.9}{2} = 3.55 \text{ gr. } H_2O \text{ vapor condensed/°F./lb. dry air}$$

$$\frac{3.55}{13.61} = 0.261 \text{ gr. } H_2O \text{ condensed/ft.}^3 \text{ saturated air/°F.}$$

or

$$\frac{0.261}{15.43} = 0.01685 \text{ gm. } H_2O \text{ condensed/ft.}^3 \text{ sat'd air/°F.}$$

$$0.81 \times 0.01685 = 0.0136 \text{ gm. } H_2O \text{ condensed/ft.}^3 \text{ sat'd air for venturi condition with 0.81°F. temperature drop.}$$

P_1 = Pressure before venturi section lb./ft.^{2}
P_2 = Pressure in venturi throat lb./ft.^{2}
T_1 = Absolute temperature before venturi section, °R.
T_2 = Absolute temperature in venturi throat, °R.
V_1 = Velocity of gas before venturi section, ft./sec.
V_2 = Velocity of gas in venturi throat, ft./sec.

A Study of a Multiple Venturi Wet Collector

Authors' Closure

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We thank Mr. Krieble and the Phoenix Iron and Steel Company for providing a specially fabricated unit adaptable to laboratory testing. In reply to Mr. Krieble's comments, experimental data obtained since formal presentation of this paper contradict certain aspects of his discussion.

In regard to spray generator performance, our studies on a single unit indicated that initial droplet velocities are close to the tangential blade velocity. Spray photographs indicated a mean droplet diam. of 400 μ and an average projection height of 5 ft. Based on the theoretical trajectory, the heights to which 200 and 500 μ droplets will rise when the projection velocity is 150 fps. are 2.5 and 6.7 ft., respectively; the assumption that V_o is approximately 150 fps. is justified. Under these circumstances, the water droplets must travel at high velocities relative to that of the gas stream within the plenum and therefore be responsible for a very significant part of the total dust removal attained within the collector. Data reported in this paper for dry Venturi operation (no upstream spray) indicate 60 to 70% removal of copper sulfate particles in a single downstream plenum chamber using but one spray generator.

Since experimental data indicate that the plenum section (acting as a simple spray washing tower) removes most of the dust, the function of the Venturi as a particle conditioning device does not appear to be an important factor in the performance of this particular collector.

The theoretical maximum quantity of water condensed upon the dust particles based upon actual temperature measurements is about the same as predicted by Mr. Krieble (0.0136 gm./ft.^{3} of gas). However, he states that the condensation process, which is limited to the converging Venturi section, produces *a very thin layer of water on the particle surfaces*. We acknowledge that such wetting might insure better cohesion between dust particles and water droplets when they collide but emphasize the fact that mere wetting does not alter the mechanics of the contacting process.

The agglomeration effects mentioned by Mr. Krieble only become important when particle concentrations are very high or retention time is very long. The concentration of an iron oxide aerosol with a mean size of 0.01 μ at an initial concentration of 1 gr./ft.^{3} (10^{12} particles/ml.) would be reduced 90% in 0.03 sec. according to Sinclair *Handbook on Aerosols*. However, this phenomena would occur naturally before the fume ever reached the collector or Venturi tubes. In addition, the large water droplets would have no effect on the Brownian diffusion or coagulation process because of their size and minimal concentration (4×10^3 droplets/ml.). Even if the average fume diam. increased to 0.1 μ (representing a 1000 fold decrease in number concentration) the presence of the water droplets would have no bearing on agglomeration. Therefore, any dust contacting that occurs within the Venturis must be due to inertial mechanisms. Calculations not shown in the present paper indicate that significant collection of 1 μ particles is theoretically possible in the Venturi tubes if the droplet concentrations are sufficiently high. These data will appear in an extended study at a later date.

It was also pointed out by Mr. Krieble that certain pyrophoric dusts or mists (Fe_2O_3 or H_2SO_4) may not acquire a liquid film due to localized heat emission. If this is true it is difficult to see how one can expect satisfactory collection of such dusts if surface wetting is considered a necessary adjunct.

Fume Control in a Fertilizer Plant—A Case History

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F. A. RETZKE
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Although a combination of granulation and drying had been found to be the best answer to the problem of caking in fertilizers, mere drying of ungranulated fertilizer, if carried to a low enough moisture content, had been found to be sufficiently promising to consider this measure under certain special circumstances.

The Saginaw, Mich., plant of an agricultural chemical company, shown in Fig. 1, presented such a set of special circumstances. Objections to caking of so-called powdered fertilizer were mounting. Granulated goods were not offered in significant amounts in the area, and the company believed that the customers would accpt some increase in dustiness of goods if caking could be reduced. According to reports from the company's staff in the area, some immediate action was desirable.

Following Battelle's suggestion, the company decided to dry its fertilizer. The only condition imposed on the design of the drying system was that it should be compatible with a future granulation system.

By the time this decision had been made, speed was important to avoid interference with the company's all-important spring production schedule. A limited number of drying tests were made by an equipment manufacturer with powdered fertilizer samples from a plant other than the Saginaw unit. Design of the dryer and dust-collection system was based on these data. Fig. 2 shows the position of this equipment in the over-all manufacturing flow sheet.

Diligent work by all the cooperating parties permitted meeting the rather close schedule, and the drying system was installed on time and was started up without any difficulties, except one: a clearly visible exhaust plume from the dryer.

Under certain weather conditions, the prevailing southwest winds caused this plume to settle in the residential areas near the plant. The plant location with respect to these houses is shown in Fig. 3.

Numerous complaints from the neighbors about the plume were registered with the plant superintendent. Management was fully aware that an air pollution problem existed and contacted the District Engineer, Division of Occupational Health, Michigan Department of Health, informing him of the nature of the problem and the action being taken. Also, in line with the company policy to maintain friendly relations in the neighborhood, the neighbors were informed of the action being taken. They were further assured that, until the corrective action could be made, the plant would not be operated during weather conditions which caused the plume to settle near the plant. This restricted operation limited the testing program which was conducted to define the problem and select the corrective equipment.

* Presented at the 49th Annual Meeting of the Air Pollution Control Association held at Buffalo, N. Y., May 20-24, 1956.

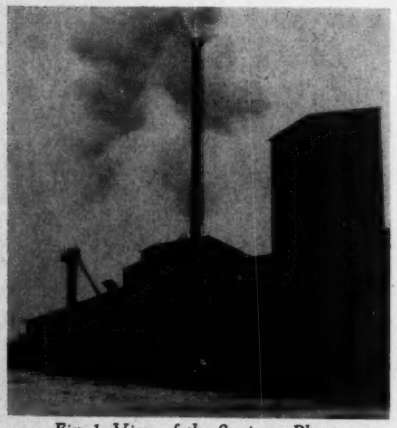

Fig. 1. View of the Saginaw Plant.

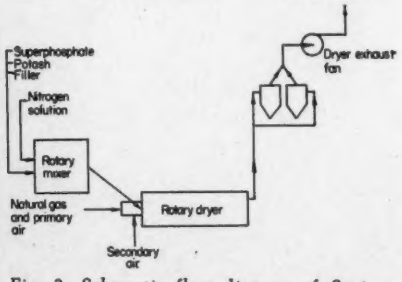

Fig. 2. Schematic flow diagram of Saginaw Plant.

The Pollution Problem

Dryer Exhaust Data

Appearance

The copious dryer exhaust plume appeared to have 3 visible components: (1) steam; (2) a fine, tan-colored dust; and (3) a component creating a bluish haze. The plume was generally carried to ground level by wind currents sweeping across the roof and the exhaust duct, about 6 ft. above the roofline; see Fig. 2. Thick, white deposits collected on objects such as windows, automobiles, shrubbery and trees. At times, a strong odor of ammonia was present and moistened pH paper indicated an alkalinity of pH 10.*

Chemical Data

Exhaust gases from the dryer were sampled at the roof outlet by methods employing an electrostatic sampler and microscopic slides. Qualitative analyses indicating the chemical character of the samples are shown in Table I.

The samples examined by X-ray diffraction showed that the dust was mostly calcium sulfate, a component of normal

* Later observations suggested that ammonia fumes may have come from an adjacent vent pipe from the fertilizer mixing system.

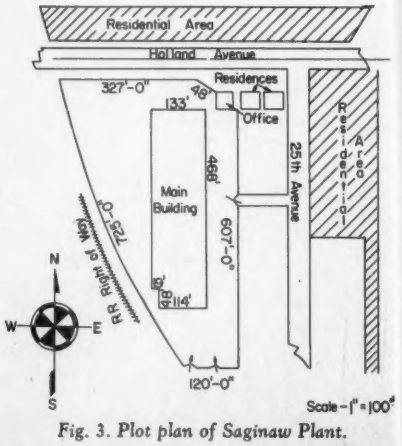

Fig. 3. Plot plan of Saginaw Plant.

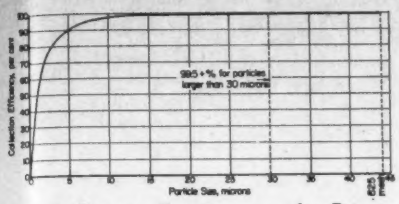

Fig. 4. Design efficiency curve for Primary Collector.

superphosphate. This suggested that fines in the superphosphate, caused by overgrinding of the phosphate rock, might be a major cause of the dust emission. Investigation of this matter is discussed in a later section.

Physical Data

Particle size distribution was determined by counts under the microscope. Gas loading was determined by weighing the material collected in electrostatic sampler tubes. Table II shows the general physical character of the dust, obtained by combining observations from 3 samples.

Two observations are of interest. First, the dust loading range of 203 to 260 mg./ft.^{3} was estimated to correspond to some 500 lb./hr. of dust, or some 15 times the maximum allowable discharge for such a system (25 tons/hr. of solids throughput) allowed by the Air Pollution Control District of Los Angeles. Second, an inspection of the efficiency curve of the existing primary dry cyclone collector (Fig. 4) showed that substantial quantities of dust in the observed particle-size range could be expected to escape such a collector.

Corrective Measures

It appeared that a secondary collector would be necessary and steps were taken to obtain one speedily. Because of the possibility that a secondary collector would operate wet, and thus flush away valuable fertilizer into a sludge pit or sewer, efforts were also made to reduce the minus 44 μ fines by changing process conditions. In addition, a study of the performance of the existing primary collector was planned to make sure that it was being operated properly. It was also felt that a stack of at least 100 ft. in height would greatly reduce the level of air pollution in the surrounding area which was attributable to the plant.

The work on process conditions will be described first, partly because most of it preceded the installation of a secondary collector and stack, and also because it permits a better organized presentation of the findings.

Process Conditions

The following variables were investigated:

1. Dryer fuel
2. Drying gas temperature
3. Dryer throughput
4. Ammoniation procedure
5. Additives in the mixer
6. Air volume in the primary collectors
7. Particle size of phosphate rock.

Many of these variables were checked, not because of strong evidence pointing to them as causes of trouble, but because tests could be performed simply and rapidly to confirm or refute the suspicions.

Dryer Fuel

During dryer warm-up periods for the shakedown runs, with no material in the dryer, a visible plume was reported. It was thought that some component in the natural gas or its products of combustion might have caused the plume. However, a temporary substitution of fuel oil for the natural gas did not improve the situation. The visible plume with an empty dryer may have been caused at that time by paint on the new equipment, or incomplete combustion of the fuel because of faulty burner or air-flow adjustments. During later operation with natural gas, the plume was almost invisible during the warm-up periods.

Drying Gas Temperatures

In the early stages of this study, it was suspected that the plume contained fumes from the volatilization of ammonium salts like ammonium chloride. Since a reduction in solids temperature would reduce or eliminate such fumes, this was attempted by lowering drying gas temperatures. Reducing the inlet temperature from 780 to 600° F. and the exit gas temperature from 230 to 200° F. in separate test runs did not visibly clear the plume. To obtain a sufficiently dry product, temperatures of about 700 and 200 were used in production runs.

Ammoniation Procedure

In the normal ammoniation process, all of the solids in a given fertilizer formula (superphosphate, potash, ammonium sulfate, and filler) are in the mixer at the time the nitrogen (ammoniating) solution is added. A different procedure was tried in which the superphosphate was ammoniated separately in the mixer, after which the other solids were added. The object of this test was to reduce the quantity of ammonium chloride that might form by the reaction of potash (KCl), free acid in the superphosphate, and nitrogen solution containing free ammonia and ammonium nitrate. It was also thought that absorption of the nitrogen solution phase by the superphosphate might reduce the amount of decomposition that could occur between potassium chloride and ammonium sulfate, present in some formulas. This change in ammoniation procedure did not improve the appearance of the plume, and it was not used for extended production runs.

Addition of Water in the Mixer

Water was added in the mixer during the ammoniation operation. It was felt that moistened material would agglomerate more, thereby reducing the amount of fines in the material to be dried. The dryer exhaust, however, did not appear to be improved and the use of water in the mixer was not continued.

Air Volume in the Primary Collectors

Admitting a larger volume of air to the collectors would reduce the dust loading in the exhaust gas stream. The higher air velocities resulting from this change could also increase the efficiency of the collectors. Opening an air bleed between the dryer and the collectors, as well as the door on the dryer-discharge hood, seemed to clear the plume slightly.

TABLE I

Chemical Character of Dust Samples

Sample	Fraction Analyzed Complete	Kind of Analysis	Elements, Ions, or Compounds Identified
27, 44		Spectrographic	Ca, Mg, P, Fe, Al
27, 44		Spectrographic	Ca, Mg, P, Fe, Al, Si
27, 44		Chemical	NH_4^+, Cl^-, $H_2PO_4^-$
1, 2, 4, 10		X-ray diffraction	$CaSO_4$, SiO_2, and an unidentified substance
27, 44	Water soluble		
1, 2, 4, 10	Water soluble		
27, 44	Water soluble		

TABLE II

Original Gas Loading and Particle Size Data

	Particle Diam. μ		Cumulative % in 0.6 to 5.0 μ range		Gas Loading mg./ft.^{3}
	Averages				
Range	Number	Weight	Number	Weight	203-260
0.6-44.0	9.0	15.0	64	3	

TABLE III

Particle-Size Comparison Between Saginaw Plant and Another Company Plant for Phosphate Rock and Superphosphate

Plant	Phosphate Rock Weight % −44 μ (325 mesh)	Superphosphate Weight %		
		−63 μ (200 mesh)	10 μ or less	5 μ or less
Saginaw[1]	100	15	3	0.75
Other plant	90	5	0.5	—

[1] Before rock grinding adjustments.

TABLE IV

Effect of Phosphate Rock Particle Size on Emission

Phosphate Rock Description	Particle Diam. μ			Cumulative % in 0.6 to 5.0 μ range		Gas Loading mg./ft.³
		Averages				
	Range	Number	Weight	Number	Weight	
"Fine"	0.6-44.0	9.0	15.0	64	3	203-260
"Coarse"	1.2-43.8	5.1	17.5	72	7	44

The procedure was not continued because of possible adverse effects on the dryer-control system.

Particle Size of Phosphate Rock

Since analysis of some dust samples indicated that the dust was almost all calcium sulfate, Battelle conducted an investigation of the particle size of the phosphate rock used to make superphosphate and of the resulting superphosphate. A comparison of the particle size of these materials with those used at another company plant is shown in Table III.

Assuming no agglomeration of these fines in the mixing or drying operations, and based on collector efficiency data, this comparison indicated that at least 1% of the superphosphate throughput would be expected to escape the collectors at Saginaw, whereas the loss would be only 0.1% at the other plant.

Therefore, the phosphate rock pulverizer at Saginaw was adjusted to produce 5 different grinds of rock dust, all coarser than that used initially. However, the superphosphate made with 3 of these grinds was not satisfactory, *i.e.*, it would not harden in the den. The coarser grind, which did make satisfactory superphosphate, contained about 10% less minus 80-mesh material than the initial fine grind, and the resulting superphosphate contained 1.7% — 200-mesh compared with 15% in the initial material. When this coarser superphosphate was used in formulating mixed fertilizer the dryer-exhaust plume appeared to contain less dust than previously, but still more than could be tolerated. Since a test showed that the solids in the dryer exhaust were reduced from over 200 mg./ft.³ to about 44 mg./ft.³ (see Table IV), the plant has continued to use the coarser grind of phosphate rock for the manufacture of superphosphate.

TABLE V

Measured Efficiency of Primary Collector

Material: 4-16-16 grade, B Superphosphate, 25 tph.	
Stack gas density	0.0597 lb./ft.³
Stack gas velocity	3860 fpm.
Stack gas volume	16500 cfm., 59000 lb./hr.
Stack gas average temperature	201°F.
Stack emission	1.61 lb./1000 lb. stack gas
Ditto	44 mg./ft.³ stack gas
"	0.68 gr./ft.³ stack gas
"	96 lbs./hr.
Material collected by collectors	4266 lb./hr.
Material escaping collectors	96 lb./hr.
Total material entering collectors	4326 lb./hr., about 8.6% of the dryer feed
Collection efficiency	97.7%

[1] Dust from only one section of the sampling probe could be removed. For dust loading calculations it was assumed that dust had deposited equally on the length of the probes.
[2] The moisture content of the gas was assumed to be constant.
[3] The particle density was determined on a sample of the stack dust minus large agglomerates.

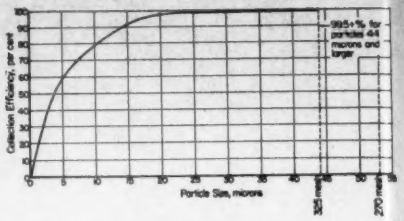

Fig. 5. Design efficiency curve of Dry Multi-Tube Secondary Collection.

Check on Primary Collector Operation

Static pressure measurements at the entrances and the exits of the primary collection system showed that pressure drops across the system were close to those recommended by the manufacturer. To make doubly sure, the bottom discharge of the system was modified to permit collection of the solids in an attempt to actually measure the collection efficiency of the system. The results of one such test run, shown in Table V, indicated an efficiency of 97.7%. This was taken as further confirmation of an earlier suspicion that little improvement could be expected from changes in operation conditions of this unit. It also explained why changes in air flow through this collector, tried as an earlier, and more readily executed, corrective measure, had a relatively slight effect.

Estimated Effect of Stacks

An attempt was made to estimate the dust-fall rate attributable to the plant in the area adjacent to it for a hypothetical installation including 100- or 150-ft. stacks. The equations of Besanquet,[1] *et.al.*, were used to calculate theoretical dust-fall rates for 3 wind velocities and at several distances from the plant. These calculations were based on 30000 cfm. of gas at 160° F. with a dust loading of 1.6 lb./1000 lb. gas (the best performance observed with only the primary collector), and assuming a mean particle diam. of 12 μ. Assuming the winds blew in any 45° sector 20% of the time, the theoretical dust fall attributable to the plant 3000 ft. away from it was only about one ton/sq. mile/month, which is below the limit of accuracy of any dust fall measurement.[2] The low level of the estimated contribution to dust fall from this source when reasonably high stacks are used is undoubtedly a reflection of the relatively small particle size of the

[1] The Spread of Smoke and Gases from Chimneys. *Trans. Faraday Soc.*, **32**, 1249 (1936).

[2] This calculation does not predict accurately the actual dust fall from a given source, but does indicate the order of magnitude of any contribution from this source to the general level of contamination.

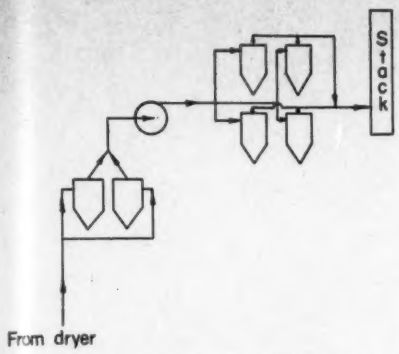

Fig. 6. Schematic flowsheet of final dust-control system at Saginaw Plant.

dust emitted from the primary collector. The addition of a secondary collector would be expected to reduce this contribution further.

Secondary Collectors

Wet Dynamic Collector

A wet, dynamic dust collector was the first choice of a secondary collector. It was available on very short notice, was reasonably priced, and the manufacturer guaranteed satisfactory performance without stipulating any major changes in the exhaust gas system.

Qualitative observations of the operation of this collector suggested substantially less dust in the dryer exhaust. The collector discharge contained substantial quantities of solids. At the time this collector was operating, measurement of solids collected in the primary collector was impossible because there was no access to its bottom discharge. Periodic sharp fluctuation in gas flow, visible emission, and pressure drop across the entire collection system suggested that friction losses might be affecting exhaust fan performance. A number of changes in duct work and operating conditions of the secondary collector were made to eliminate all obvious sources of excessive friction.

When all these steps had been taken, the pressure drop across the wet collector was still found to be above that promised in the manufacturer's specifications. This pressure drop seemed to limit gas velocities and may have affected the collection efficiency in both the primary and the secondary collector.

Although not enough measurements were possible at the time to confirm the above hypothesis, it was decided to return the wet dynamic collector to the manufacturer for the following reasons: (1) A pressure-drop limit was a part of the guarantee; (2) Installation of a larger fan and motor, even if it made the system work, would increase not only investment, but would also increase power consumption and thus operating cost, and (3) Delivery of a larger fan and motor would take about as long as delivery of some alternate secondary collectors.

TABLE VI
Secondary Dust Collectors Considered for Saginaw

General Type	Estimated Cost dollars	Reason for Elimination
Venturi-Type	Not obtained	High pressure drop, 25 in.; 125 hp. fan; 130 gpm. of 140 psig. water required.
Electrostatic	52000	High cost; additional heat and power required for operation; promised delivery too late.
Bag Filter	16400	High cost; bag fabrics required impractical; air temperature limitations of 185° F. dry bulb, 140° F. wet bulb.
Dry Multitude	17591	High cost; pressure drop 8 in.; potential cleaning problem of 184 4½ in. diam. tubes.
Dry Multitude	7600	Not eliminated. Cheapest first cost, low pressure drop, easy maintenance, efficiency estimated as 97% (within 1 or 2% of other collectors). Prompt delivery promised.

Other Secondary Collectors

Selection of an alternate secondary collector was based on the following general factors:

(1) Installed cost;
(2) Collection efficiency;
(3) Pressure-drop requirements within the capacity of the dryer exhaust fan;
(4) Relatively low water requirements;
(5) Minimum cleaning and maintenance requirements; and
(6) Installation before the fall production season.

The types of collectors considered, and general information concerning them that affected the choice, are listed in Table VI. After reviewing these data, it was decided that the dry multitube collectors, consisting of four 2-ft. diam. units, came closest to being the optimum solution under the circumstances. An order for this equipment, for delivery in about 6 wk., close to the specified date, was placed. Fig. 5 shows a design efficiency curve for this collector.

Installation of a Stack

A stack by itself was not expected to reduce the emission from any system. However, as indicated by the previously presented estimates, the nuisance from a given emission can be reduced by taking advantage of the dispersion made possible by an elevated discharge. It was therefore decided that, whatever the efficiency of any secondary collector might be, a stack would be a desirable addition to the plant.

The theoretical stack dispersion calculations previously described indicated that a stack of only 100 ft. in height would reduce to low levels any dustiness in the area attributable to the plant's operation. This contribution would be further reduced by the installation of secondary collectors. It was felt rather arbitrarily that a minimum stack height of 100 ft. should be considered. However, since the theoretical calculations do not consider all of the effects of terrain and building configuration, it was suggested that a 150-ft. stack would be preferable. Practical consideration resulted in the selection and installation of a 100-ft. stack. The final dust control system, including the stack, is shown schematically in Fig. 6.

Performance of the Secondary Collector and Stack

Initially the secondary collector was operated as a dry collector. The efficiency was estimated to be 97%, based on the particle-size analysis of the dust emission from the primary collector, made during the equipment-selection tests. However, a performance check by the manufacturer indicated that the efficiency of the secondary collector was only 58%, based on a collection of 56 lb. of dust/hr. and a 96 lb./hr. dust emission from the primary collector, obtained in the equipment-selection test. It appeared to the manufacturer that the particle size of the dust entering the secondary collector was much finer than shown by the analysis of the equipment-selection-test sample and that the efficiency of the secondary collector could not be expected to approach the estimated 97%. The discrepancy in the particle size may have resulted from the tendency of the dust to agglomerate in the sampling apparatus and also from the tendency to weight a microscopic count in favor of large-sized particles.

In view of this performance check, management was concerned that the dust emission from the secondary collector might still prove objectionable to the neighbors. The manufacturer recom-

mended putting to use the 28 water nozzles already installed in the inlet box of the collector. Dust emission appeared to be reduced significantly by operating this unit as a wet collector. No quantitative measurements of emission have been made since the unit has been installed. However, no complaints have been received from any of the neighbors, and a representative of the Michigan Department of Health has verbally commended the company for correcting the situation and also expressed surprise at the extent of the corrective action.

As shown in Fig. 1, the plume from the 100-ft. stack is still quite visible. Observers reported, however, that much of this plume appeared to be water droplets which evaporated rapidly, leaving very little, if any, haze in the area beyond the plant proper. Fig. 1 seems to confirm these observations.

Venturi Scrubbers for Cleaning Cupola Gases*

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The purpose of this paper is to outline a pilot scale test performed with a Venturi Scrubber for cleaning cupola gases at a large midwest manufacturer of farm equipment.

The gray iron cupolas involved in the test were of the standard open topped variety in common use today. They are cylindrically shaped, brick lined structures roughly 8 ft. in diam., and somewhat like smoke stacks in appearance. Air is blown under pressure through tuyeres located near the base and the charge is loaded through a large rectangular opening in the side approximately 18 ft. above the base.

During normal operation thick rust colored clouds of fume are emitted from the tops of the cupolas. The larger particles, up to ¼ in. in size, shower down in the immediate vicinity and a 2 to 3 man team is required to keep the roof clean around the stacks. As the prevailing winds carry away the fume, the remaining heavy particles settle leaving a light persistent cloud of fine particles trailing off in the distance.

The volume of fume exhausted by each cupola varies between 25000 and 35000 scfm. and dust loadings run in the range 1 - 2 gr./scf. (corrected to 12% CO_2).

Principle of Venturi Scrubber Operation

The essential parts of a Venturi Scrubber System are a Venturi tube, an entrainment eliminator and an induced draft fan. (Fig. 1) The purpose of the Venturi shape is to accelerate the gas stream to a velocity of 200 - 400 ft./sec. with a minimum of friction and velocity head loss. The scrubbing fluid is introduced at the throat in the form of relatively heavy jets a little larger than the diam. of a pencil.

Only enough hydraulic pressure is needed to force the jet to the center of the throat—25 to 30 psig. is sufficient for nearly all commercial applications. The high velocity gas stream instantaneously ruptures the water jets and fills the throat area with a very turbulent cloud of spray. The concentration of tremendous numbers of droplets in the restricted throat area make the free path of a dust particle a maze of tortuous turns. This, combined with the high initial velocity difference between the particles and droplets, promotes efficient impaction and agglomeration.

Once the fine dust particles are captured by the droplets, they can be removed from the gas stream relatively easily in a simple separator. In our case, we use an entrainment separator in which the gas enters tangentially, spinning the water droplets against the wall. They drain by gravity and may be either recycled or sewered.

For difficult scrubbing jobs, that is, jobs in which the particulate matter to be removed is mostly under 1 μ, the Venturi requires a high pressure exhauster.

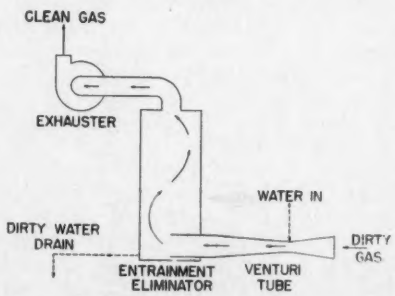

Fig. 1.

Nearly all of this pressure drop takes place right here at the throat. The greater the amount of power consumed at this point, the greater the gas cleanliness which can be achieved. This is the outstanding characteristic of a Venturi Scrubber in that even for very difficult applications, high cleanliness can be obtained if sufficient power is furnished. Also, for any given scrubber installation, increased scrubbing efficiency can be attained by the addition of more fan power and with no need to alter the physical size or shape of scrubbing equipment.

Fig. 2 is from a photograph taken looking downstream into a Venturi throat. Note how the water jet streams are quickly dispersed into a homogeneous mass of spray.

Venturi Scrubbers are relatively new. The original patents were applied for as recently as 1946. The high efficiencies and small maintenance requirements of these scrubbers has led to their rapid ingress into many applications formerly handled only by such high efficiency dust removal equipment as electrostatic precipitators, baghouses and disintegrators. Venturi Scrubbers are now handling gas volumes as small as 200 cfm. and as large as 145,000 cfm. in single units. Over 150 of these scrubbers are now in operation on a large variety of fumes requiring special construction techniques for corrosion and erosion resistance. As a partial list of materials, units have been constructed of mild steel, stainless steel, aluminum, nickel, copper, porcelain, plastics, and with rubber, plastic, acid brick and silicon carbide brick linings.

One of the unusual features about a Venturi Scrubber is the ability of a small pilot unit to give identical scrubbing results to a full scale installation. At one

* Presented at the 49th Annual Meeting of the Air Pollution Control Association held at Buffalo, N. Y., May 20-24, 1956.

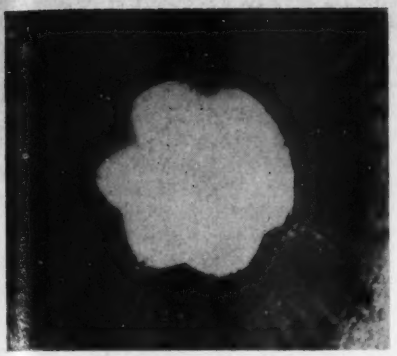

Fig. 2.

Fig. 3.

Fig. 4.

Fig. 5.

plant where an extensive set of scrubbing tests were taken to determine the removal efficiency of phosphoric acid fume, the full scale plant results checked the pilot unit tests to within a few tenths of 1%. This characteristic has made it possible to perform tests with a portable 500 cfm. pilot unit and to use the result directly, without extrapolating or adding factors, for the design of larger units.

Fig. 3 shows a typical installation of a Venturi Scrubber for cleaning blast furnace gas. Fig. 4 is a view of an installation for removal of lead fume from a lead reclaiming blast furnace.

Pilot Unit Tests

The purpose of the cupola pilot unit tests was:

1. To observe the effluent appearance.
2. To determine if a Venturi Scrubber could reduce the dust in the effluent to below the maximum allowed by local air pollution ordinances.
3. To determine the optimum operating design for a full scale unit.

To obtain this data, the 500 cfm. pilot unit was placed on the roof of the cupola building and piped up so as to be able to exhaust a representative sample of gas from either of two cupolas. Six in. diam. sampling ducts were located approximately 8 ft. below the tops of the cupolas. To compensate for variations of flow patterns in the stacks, one sampling duct was placed at the center of the stack and the other near the periphery. The volume of gas exhausted by the pilot unit (Fig. 5) was 1½ to 2% of the total gas volume.

The visual effects were simply determined. While maintaining the gas flow close to 500 cfm., the amount of water to the throat was gradually increased, thereby increasing the scrubbing power consumption. When viewed against a bright sky the effluent, after steam evaporation, was light blue at low power consumption and invisible at high power consumption. When viewed against a dark background, a very faint blue haze was visible at all times. The unscrubbed gas from the cupolas was rust colored and remained plainly visible as it trailed off in the distance.

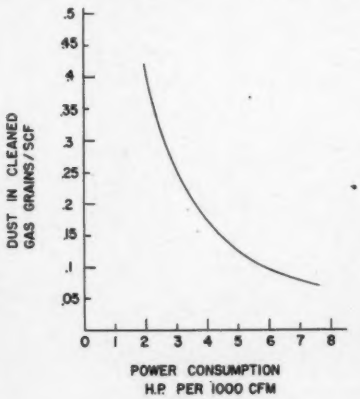

Fig. 6.

Fig. 6 illustrates how the quantitative clean gas dust loadings varied with increasing power consumption. You can see from this that, even at lower power ratings, the Venturi more than satisfied the local ordinance cleaning requirement which was 0.48 gr./scf. Note also how, at low power ratings, a small increase in power sharply reduces the dust loading while at higher ratings, fume reduction requires more and more power. This type of curve is characteristic of nearly all Venturi Scrubber applications and is independent of the volume of gas handled.

Dust Particle Sizes & Chemical Analyses

To determine the points for this curve, samples were obtained by exhausting small portions of the cleaned pilot unit gas through paper filters. Fig. 7 is a photomicrograph of dust scraped from a cleaned gas filter sample. The particles are spherical in shape and between 0.05 and 0.22 μ in size. Fig. 8 is a photograph of dust taken from the gas entering this scrubber.

A qualitative spectrographic analysis of inlet dust samples indicated iron and

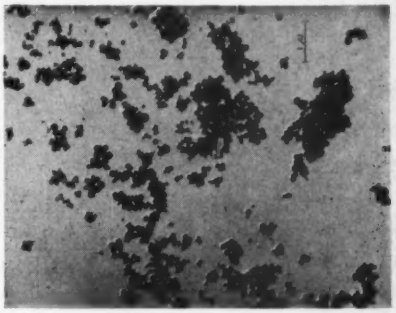

Fig. 7.

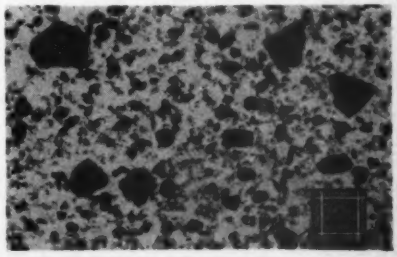

Fig. 8.

silica to be the main constituents.

Recycle Tests

To test the plugging characteristics and the corrosiveness of recirculated scrubbing solutions, a 55 gal. drum was used as a recycle tank in four of the pilot unit tests. After 10 hr. of operation, only one of the 6 jets showed signs of plugging. Since these are less than one half the cross-sectional area of full scale scrubber jets, it was evident that no serious trouble would result from this source. The acidity of the recycle solution varied between pH.'s of 3 and 4.5 with the average value close to 4.0. A sample of the recycle liquor was filtered and the solids were dried and analyzed as follows:

Fe	9.45%
Zn	5.62
Cr	4.54
SiO_2	44.15
Loss On Ignition	8.97

This checked the previous inlet dust analyses and confirmed that iron and silica were the primary fume contributors. Further, the spherical shape of the particles is typical of high silica fumes.

Materials of Construction

Because most cupola gases become corrosive on wetting (due to sulfur in the coke) special construction is required. Though stainless steel is satisfactory, it has been found to be more economical to design for mild steel gunited with an aluminous cement for the construction of less intricate shapes. The throat of the Venturi, however, with its multitude of jets and finer tolerances, would be fabricated of stainless steel. The exhaust fan and recycle pumps for these units would also be constructed of stainless steel.

Summary

The Venturi Scrubber can clean cupola gases so that dust loadings are far below most local ordinance requirements. The optimum design, of course, is for a scrubber which will consume just enough power to meet the requirement. A very wide variety of these requirements can be met in a single Venturi Scrubber design by varying the power supplied by the exhauster *i.e.*, the size and speed of the fan wheel and motor. Even when operated at relatively low pressure drops, the Venturi can meet most code requirements. Where the water supply is short, recycle can be used with little or no extra maintenance required for the scrubbing system. If necessary, by the use of a filter press, the collected dust can be disposed of in the form of a readily handled mud.

Properties and Control of Electric-Arc Steel Furnace Fumes*

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The furnaces employed in electric-arc melting practices in the steel industry are normally of the 3-electrode, direct-arc type (Fig. 1). Two fundamental types of melting processes, acid and basic, are commonly employed. Both the acid and basic process cycles are essentially batch operations requiring $1\frac{1}{2}$ to 4 hr. The process cycle consists of the melt-down, the molten metal period, the boil, the reducing or refining period and the pour.

The impetus, in the steel processing industry due to the development and expanding use of higher alloy and stainless steels, has led to the increasing use of the basic-lined furnace.[1] This furnace can employ both high- and low-grade alloy scrap and plain carbon scrap to produce steels that meet the stringent chemical, mechanical, and purity specifications required today.

On the other hand, the steel foundry industry uses the more economical acid-lined electric-arc furnace which meets its needs with regard to control of operations and quality of products.[1] Hence, the acid furnace is seldom used outside of steel foundries and forging shops whose specifications for straight carbon, and high- and low-alloy steels can be met by this process.

Fig. 1. Typical Electric-Arc Steel Melting Furnace

Quantity of Fume Emitted

From the furnace operations listed in Table I, a mean quantity of 10.6 lb. of fume is generated/ton of metal melted in electric-arc steel melting furnaces, the range being from 4.5 to 29.4 lb./ton. Emissions as high as 37.8 lb./ton have been reported.[2] The wide variations in reported fume emissions are attributable to the following factors: type of furnace process, furnace size, formulation of charge, quality of scrap, cleanliness of scrap, sequence of charge additions, melt-down rate, metal refining procedure, and pouring temperature.

Any effects of furnace process or furnace size on fume emission are not obvious in the data presented. No significant difference in fume emissions from acid and basic furnace processes is ap-

(1) *The Making, Shaping and Treating of Steel*, 6th ed., 480-521, United States Steel Corp., Pittsburgh, Pa. (1951).

* Presented at the 49th Annual Meeting of the Air Pollution Control Association held in Buffalo, N. Y., May 20-24, 1956.

(2) C. A. Faist. Remarks, A.I.M.E. *Electric Furnace Steel Proc.* 11, 160-1 (1953).

parent. It has been stated[3,4] that the quantity of fume emission/ton of metal processed increases with furnace size, but this relationship also is not evident here.

The quality of scrap charged, however, is of extreme importance, since the inclusion of large quanities of lower boiling nonferrous metallic impurities in the melt will inevitably lead to high concentrations of oxides of these metals in the fume.[5,6] The cleanliness of the scrap likewise is an important factor because most impurities (paint, oil, grease, wood, fabrics, *etc.*) will be volatilized at the high temperatures existing within the furnaces.[7]

Fume emission may be affected further by the sequence of charge additions to the furnace. Metal oxide fumes from the melt are normally decreased after slag additions, because of the slag blanket formed.[8,9] Impurities may then be included within the slag rather than vaporized to the furnace atmosphere. Partially offsetting this reduction is the volatilization of the newly added slag components.

The method employed for metal refining also has a pronounced effect on fume emission. An oxygen lance leads to higher fume releases[10] because of the breaking of the slag film by effluent bubbles and because of the extremely high temperatures[11] reached during this operation. These temperatures lead to increased volatilization of the melt constituents. A mill-scale boil or a spontaneous, noninitiated boil has a similar but less pronounced effect. Another recognized factor affecting quantity of fume emitted is the pouring temperature. High pouring temperatures required for small or thin-walled castings lead to greater fume emission because of the rapid increase of the vapor pressure of the molten components with temperature.

TABLE I
Electric-Arc Steel Furnace Emission Data

Case	Rated furnace size, tons	Average melting rate, tons/hr.	Cycle time, hr.	Fume emission/ton melted, lbs./ton	Furnace process	Reference
A	50	18.3	4	9.3[c]		5, 7
	75	23.5	4	18.6[d]	Basic, single slag	
	75	23.5	4			
B	50[a]	14.4	4	7.6		16
	50[a]	13.6	4	6.9	Basic, single slag	
	75[a]	21.9	4	12.3		
	3	1.5	2	12.6	Acid, oxygen blow	
	3	1.1	2	7.6	Acid, oxygen blow	
	6	3.1		10.4		
	10	6.6	2	5.5	Basic, oxygen blow	
	10	5.4	2	5.2	Basic, oxygen blow	
	2[b]	1.5[b]		13.4		
C	3	1.9	2	4.5	Acid	6
	3	1.6	2	5.8	Acid	
	3	1.9	2	5.7	Acid	
	6	2.6	2.33	15.3		
	6	3.0	2	12.8		
D	18	5.4	3	6.1		15
E	6	4.1	1.2	29.4	Acid, single slag	2, 18
F	3	1.8	1.75	12.7	Acid, single slag	20

(a) Refer to same furnaces as Case A.
(b) Two 2-ton furnaces operating in parallel.
(c) Average for one 50-ton and two 75-ton furnaces processing normal scrap.
(d) Average for one 50-ton and two 75-ton furnaces processing dirty, sub-quality scrap.

While quantitative effects of all of the above factors are not apparent from data presented in Table I, the significance of these factors is clearly shown in either the previous literature or the original data analyzed for this paper. Coulter[5,7] performed several tests (Table I-A) under identical operating conditions except for differences in cleanliness and quality of the scrap charged. The amount of fume emitted/ton of metal melted increased 100% when dirty, sub-quality scrap was used. Substantiation of these effects is reported by Kane and Sloan.[6] Their tests (not given in Table I) show an increase of over 40% in the amount of fume released/ton of metal processed when poorer scrap was charged to the furnace. (The actual fume increase was over 40% since fumes evolved during a full quarter of the melting cycle were lost because of a defective collecting thimble.)

In addition to the above factors, the effects of several other variables on total fume emission may be hypothesized, although not substantiated by experiment. The formulation of the charge may be a factor, as the higher the proportion of sub-quality scrap contained in the charge, the greater the amount of impurities in the furnace. These impurities are, in part, subject to volatilization; hence, fume discharge increases. Also, since the rate of heat flux to the bath increases in proportion to the rate of melt-down, higher temperatures exist in the molten pool when the higher melt-down rates are employed. The resulting increased temperature should cause greater over-all fume emission.

Discharge Rate and Composition of Fume

The effects on fume emission rate and chemical composition of the fume appear to be a function of the melting cycle phase and the charge formulation and quality. Erickson[8] and Assel[3] have reported that fumes may analyze 40 to 50% iron oxide during melt-down. Erickson further states that when the scrap is completely melted, the iron oxide content of the fume drops to well below 20%, with the remainder being composed of oxides of calcium, silicon, phosphorous, manganese, and sulfur. Assel also reports that after the slag is made up, the iron oxide content may fall as low as 5%, with the calcium oxide content of the fume increasing to the 45-50% range.

The rate of fume release appears to reach a peak during the boil and refining periods. When an oxygen lance is employed, dense fumes of hematite and magnetite are produced.[10] As previously noted, this peak fume release is less pronounced when a mill scale or a spontaneous boil is employed. It can be said in general that during refining, fume rates are high, reaching a final peak as pour temperature is approached.

In addition to the variations in fume composition resulting from melting cycle

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(3) W. E. Lewis. Remarks, A.I.M.E. *Electric Steel Furnace Proc.* 10, (Dec. 1952).
(4) G. L. Allen, F. H. Viets, and L. C. McCabe. Control of Metallurgical and Mineral Dusts and Fumes in Los Angeles County, California, *Bureau Mines Inf. Circ.* 7626, 49-50 (April 1952).
(5) R. S. Coulter. Bethlehem Pacific Coast Steel Corp., Personal Communication (April 24, 1956).
(6) J. M. Kane and R. V. Sloan. Fume Control —Electric Melting Furnaces. *Amer. Foundryman* 18, No. 5, 33-5 (Nov. 1950).
(7) R. S. Coulter. Smoke Dust, Fumes Closely Controlled in Electric Furnaces. *Iron Age* 173, 107-10 (Jan. 14, 1954).
(8) E. O. Erickson. Dust Control of Electric Steel Foundries in Los Angeles Area. A.I.M.E. *Electric Furnace Steel Proc.* 11, 157-60 (1953).
(9) W. J. Assel. Remarks, A.I.M.E. *Electric Steel Furnace Proc.* 10, 47 (Dec. 1952).
(10) M. P. Fedock. Melting Practice and Refractories Performance in Basic Electric-Arc Furnaces. *Industrial Heating*, 20, 135-140 (Jan. 1953).
(11) J. M. Kane. The Application of Local Exhaust Ventilation to Electric Melting Furnaces. *Amer. Foundrymen's Soc. Trans.* 52, 1351-6 (1944).

phase, the effects of charge formulation and quality are significant. The inclusion in the charge of nonferrous metallic impurities will result in the oxides of these metals being present in the fumes emitted. Coulter[7] has reported the following average composition of fume produced during an entire melting cycle:

Component	Wt. %
ZnO	37
Fe	25
CaO	6
MnO	4
Al_2O_3	3
SO_3	3
SiO_2	2
MgO	2
CuO	0.2
P_2O_5	0.2

As noted, the composition includes a high percentage of non-ferrous metallic oxides in addition to those constituents normally expected in the fume emission. Further substantiation that metallic impurities in the charge produce nonferrous oxides in the fume is found in the work by O'Mara,[12] who reports approximately 25% zinc oxide present in one such fume.

Physical Properties of the Fume

Certain physical properties are characteristic of the solid emissions from electric-arc steel melting processes. Specifically, these particles have a strong tendency to adhere to both natural and synthetic fabric surfaces,[8] they possess a high angle of repose,[8] they are difficult to wet,[13,14] and they possess a high electrical resistivity.[8,15] These properties limit the applicability of control equipment, and specific consideration for offsetting these inherent limiting qualities of the fume must be provided for in satisfactory control installations.

Furthermore, particle-size distribution measurements made by the Los Angeles County Air Pollution Control District[16] and by Erickson[8] (Table II-A,B) show that electric-arc steel furnace fumes are predominantly (approximately 70% by weight) in the range below 5 μ. Electron photomicrographs[4] have shown that 95% by number of the particles in such fumes are less than 0.5 μ in diam. The presence of appreciable percentages by weight of larger particles as determined by sedimentation procedures[8,16] is undoubtedly due to the high agglomerating tendency of this type of fume.

Collection of the Fume

The type of hooding provided in each melting furnace installation will determine the temperature and volume relationship of the effluent gas to be processed. Three types of control hoods are in general use: (1) canopy-type hoods, (2) enclosing or roof ring hoods, and (3) direct furnace taps. Canopy hoods located above the crane-way offer the least interference with operating procedure; but, to capture furnace effluent efficiently, large volumes of indraft air are required, resulting in lowered gas temperatures. Roof ring hoods closely fit around the charging door, pouring spout, and electrodes and have a disconnecting flange in the exhaust duct to allow for furnace movement. A modification of this type of hood is the direct furnace tap in which the furnace itself serves as a refractory-lined hood. These last 2 types of hood require smaller volumes of indraft air for efficient collection, and higher effluent gas temperatures result.

The characteristically small particle size of electric-arc steel furnace fume precludes the use of dry centrifugal collectors, settling chambers, *etc.* when high efficiencies are required. Furthermore, those types of control equipment capable of giving high efficiency performance must operate within the following specific limitations:

(1) wet scrubbers require high power inputs,

(2) baghouse collectors need special provisions for increasing the effectiveness of the shaking mechanisms and for controlling the gas temperature and humidity, and

(3) electrical precipitators must have adequately conditioned gas.

High efficiency scrubbing systems can be used for the control of electric-arc steel furnace fumes. However, high power requirements tend to negate their use. In one installation the fume collection system consists of a spark box, a washer, a disintegrator (a high-efficiency water-fume contactor), and a moisture eliminator.[17] A gas vol. of 50000 cfm. at 60°F. is handled with an inlet fume loading of 1.12 gr./ft.^{3} The material, which is collected at 98 + % efficiency, analyzes just over 50% Fe_2O_3. Horsepower requirements for this collection system, 13.3 hp./1000 cfm., are high in relation to other high-efficiency collection installations.

Use of Electrical Precipitators

Fumes from a 50-ton and from two 75-ton furnaces (Table III-A) are collected by a high-efficiency plate electrical precipitator utilizing mechanical full-wave rectification.[5,7] The furnaces are operated under a draft of 0.02 in. H_2O with the fumes being removed through direct furnace taps to a 2-stage evaporative cooler-conditioner. The precipitator handles 105,000 cfm. at 127°F. with an inlet fume concentration varying between 0.68 and 1.35 gr./ft.^{3} Collections of over 97% efficiency are realized using an electrode length to gas volume ratio (L/V) of 6.8 sec./ft.^{2} and a gas velocity of 3.9 ft./sec., giving a gas retention time in the equipment of 4.6 sec. In the particulate concentration range concerned, collection efficiencies should be relatively independent of inlet loadings.

A second installation (Table III-B), while designed to employ gas conditioning, is actually being operated without such conditioning because of a reduction in plant furnace capacity. The equipment is an expanded metal plate (high efficiency) electrical precipitator, utilizing mechanical full-wave rectification.[15] A ring-type hood directs the furnace effluent through a radiation cooler after which tempering air is added to reduce the gas stream temperature to 80°F. Approximately 33500 cfm. then enters the precipitator at this temperature with a fume loading of 0.115 gr./ft.^{3} The L/V

[4] See Footnote 4, page 221.

TABLE II

Electric-Arc Steel Furnace Fume Particle-Size Distribution, Weight Percent

Size range, μ	Case A	Case B	Case C
0-3			18
0-5	71.9	67.9	
3-11			64
5-10	8.3	6.8	
11-25			7
10-20	6.0	9.8	
>25			11
>20	13.8	15.5	
	100.0	100.0	100
Reference	16	8	13

[7] See Footnote 7, page 221

[8] See footnote 8, page 221.

[12] R. F. O'Mara. Dust and Fume Problems in the Steel Industry. *Iron and Steel Eng.* **30**, No. 10, 100-6 (Oct. 1953).

[13] H. Dok. Smog Control in the Steel Industry. *Air Repair*, **5**, No. 1, 23-6 (May 1955).

[14] H. Dok. Smog Control in the Foundry. *Amer. Foundryman*, **26**, No. 12, 46-9 (Dec. 1954).

[15] H. M. Pier and H. S. Baumgardner. Research-Cottrell, Inc., Personal Communication, April 17, 1956.

[16] Los Angeles County Air Pollution Control District, Los Angeles, Calif. Unpublished Data, 1950-1951.

[5] See footnote 5, page 221.

[17] B. D. Bloomfield. Appraisal of Air Pollution Control Installations. Presentation at Joint Air Pollution and Engineering Session, American Industrial Hygiene Assoc. Meeting, Phila., Pa. (April 26, 1956).

TABLE III
Collection of Electric-Arc Steel Furnace Fumes

Electrical Precipitator Data		
Case	A	B
Operational Data		
Inlet gas vol., cfm.	105,000	33500
Inlet gas temperature, °F.	127	80
Absolute humidity, lb./lb. dry gas	0.045	Ambient
Inlet fume conc., gr./ft.³	0.68[a] - 1.35[b]	0.115
Electrical Precipitator Data		
Type	High eff. plate	Exp. metal plate
Rectification	Mech., full wave	Mech., full wave
Size	30 ducts, 10 in. x 18 ft. x 18 ft.	19 ducts, 8¾ in. x 17 ft.-6 in. x 18 ft.
Gas velocity, fps.	3.9	2.3
Gas retention time, sec.	4.6	7.8
Electrode Length, ft.	11880	7550
L/V ratio, $\frac{\text{Electrode length}}{\text{Volumetric rate}}$, sec./ft.²	6.8:1	13.6:1
Gas Conditioner Data		
Type	2-Stage evaporative cooler	Radiation and tempering air cooler
Collection Efficiency	97+%	92%
References	5, 7	15

[a] Average for one 50-ton and two 75-ton furnaces processing normal scrap.
[b] Average for one 50-ton and two 75-ton furnaces processing dirty, sub-quality scrap.

ratio in this case is 13.6 sec./ft.², and gas retention time is 7.8 sec. Gas velocity is 2.3 ft./sec. and a collection efficiency of 92% is obtained which, as in the case above, should also be relatively independent of inlet loading.

Electrical precipitator efficiencies may be correlated by a general equation of the form:

$$E = 1 - K^{(L/V)}$$

where
E = fractional collection efficiency
K = precipitation constant (always less than unity)
$^{(L/V)}$ = electrode length/volumetric flow rate

From this equation it is seen that high L/V ratios and low values of K will favor high collection efficiencies. The K value is dependent upon the resistivity of the fume for a specific degree of gas conditioning. Despite the more favorable L/V ratio found in Case B (Table III), a lower collection efficiency is realized. From the general equation it is evident that this lower efficiency is most likely attributable to the higher value of K resulting from inadequate gas conditioning.

Use of Baghouse Collectors

The first baghouse installation tabulated in Table IV-A handles 50000 cfm. of 124° F. gas from one 1-ton, one 3-ton, and two 6-ton electric-arc steel furnaces.[13] The total of roughly 40000 cfm. from the four furnaces is normally tempered with 10000 cfm. of cooling air to reduce its temperature to that required for baghouse operation. The 4-section baghouse contains 26174 ft.² of orlon bags operating at a filter velocity of 1.91 ft./min. Each section is shaken under back pressure 10 seconds each hour. The bag pressure-drop changes from a maximum of 4 in. H_2O before shaking to 2 in. H_2O after shaking. Efficiencies of 98+% are readily obtained.

The second baghouse tabulated in Table IV-B contains 654 bags in 3 sections, handling a vol. of 16000 cfm. at 130-180° F. from a 6-ton acid furnace.[2, 18] The furnace employs single-slag operation with an oxygen lance during the boil. No specifically designed gas cooler is in use, but a long duct run serves as an effective radiation cooler. The total filtering area is 8937 ft.² and the operating filter velocity is held to 1.79 ft./min. Under these conditions the maximum bag pressure-drop varies from 4 to 5½ in. H_2O. Bag shaking takes place for 3 min. at the end of each hour's operation. Actual efficiencies have not been measured but are assumed to be 98% or better. Cotton bags rotted after only short usage and have been replaced with orlon bags 5 in. in diam. and 124 in. long. The deterioration of cotton is probably caused by the presence of ozone and oxides of nitrogen in addition to the acidic nature of the gas.[19]

The final baghouse operation tabulated in Table III-C processes the effluents from a 3-ton furnace in which an acid, single-slag melting cycle is used in combination with a mill-scale boil.[20, 21] The gas passes through an enclosed roof hood and then is cooled by radiation and air tempering to 142° F. before it enters the baghouse. Very nearly 12000 cfm. are cleaned at an average inlet loading of 0.22 gr./ft.³ Collection efficiencies of

[13] See Footnote 13, page 222.

[2] See Footnote 2, page 220.

[18] C. A. Faist. Burnside Steel Foundry Co., Personal Communications. April 25, 1956.

[19] Control of Emissions from Metal Melting Operations. Amer. Foundrymen's Soc., Des Plaines, Ill., p. 21.

[20] E. F. Anderson. There Are Indirect Benefits from the Furnace Fume Collector. *Foundry* **83**, 152-3 (Sept. 1955).

[21] E. F. Anderson. Wheelabrator Corp., Personal Communication. April 30, 1956.

TABLE IV
Collection of Electric-Arc Steel Furnace Fumes

Baghouse Collector Data			
Case	A	B	C
Operational Data			
Inlet gas vol., cfm.	50000	16000	11990
Inlet gas temperature, ° F.	124	130-180	142
Absolute humidity, lb./lb. dry gas	Ambient	Ambient	Ambient
Inlet fume conc., gr./ft.³		0.88	0.22
Baghouse Collector Data			
Type	Sectioned-tubular	Sectioned tubular	Sectioned-tubular
Filter medium	Orlon	Orlon	Orlon
Filter area, ft.²	26174	8937	
Filter velocity, ft./min.	1.91	1.79	
Shaking cycle, min.	60[a]	60	105
Pressure drop, in. H_2O	4	4 - 5.5	1.6
Collection Efficiency	98+%	98+%	99+%
References	13	2, 18	20, 21

[a] Combined with reverse air flow.

over 99% are reached in the sectioned baghouse containing tubular orlon bags. The pressure drop through the bags increases from 0.6 in. H_2O after shaking to 1.6 in. H_2O just before the shaking cycle starts. The bags are mechanically shaken for 3 min. each time the furnace is tapped.

From the 3 baghouse operations cited, the following generalities are apparent:

(1) tubular orlon filter bags have proven satisfactory;

(2) in spite of the high angle of repose and the adhering tendency of electric-arc furnace fumes, bag cleaning can be successfully accomplished by automatic shaking alone or in conjunction with reverse air flow;

(3) pre-cooling of the effluent gas stream is necessary, since available filter media will not resist extreme temperatures (Orlon will withstand temperatures as high as 350°F. Woven glass fiber filter bags can withstand temperatures of 500°F. but cannot be subjected to vigorous shaking).; and

(4) filter velocities on the order of 2 ft. /min. are common.

Recommendations for Future Work

Available data concerning emissions from electric-arc steel melting furnaces are limited. There is a lack of details on process type, charge composition, meltdown rate, pouring temperature, and other variables associated with furnace operation. Because of this, realistic correlations enabling accurate predictions of fume emissions cannot be developed. Therefore, future studies should include these operating variables in as minute detail as possible.

At present, little is known about the changes in fume characteristics with respect to process phase. Chemical composition and emission rates should be determined during different periods in the melting cycle for various furnace processes. Such work should assist in developing more economical fume collection systems by indicating the duration of critical collection periods during which extreme conditions are encountered. Further, in this regard, operating information on existing fume collection installations will aid in determining optimum collection parameters.

In order to treat electric-arc steel furnace fume collection theoretically, accurate particle-size distributions for each phase of the melting cycle must be known. Since appreciable weight fractions of fume occur in the range below 5 μ, a more detailed breakdown in this range would be advantageous.

Conclusion

An attempt has been made to assess the properties and quantities of emission from the electric-arc steel melting furnaces and to evaluate control systems in terms of these emission characteristics. The data considered in performing this study have, in the main, originated from previously unpublished sources. Because of the wide variation in source material, it is the opinion of the authors that the furnace capacities and operating techniques covered are representative of the industry as a whole, and as such the data presented should be useful in future evaluation of this problem.

The Operation and Use of the Titrilog and the Autometer

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The purpose of this presentation is to describe the operation and uses of the 2 most commonly employed automatic instruments now available for the measurement of sulfur dioxide. These are the Titrilog and the Autometer. The Titrilog utilizes chemical absorption and oxidation measured in terms of potentiometric titration, with the titer generated electrolytically. The Autometer also utilizes chemical absorption and oxidation, but the concentration is measured as the change in conductivity of the absorbing solution instead of the quantity of a titer.

The Titrilog

Briefly, the principles of operation of the Titrilog are as follows (Fig. 1): Air is drawn continuously at a suitable flow rate, perhaps 50 or 100 ml./min., into a titration cell. This cell is divided into 2 compartments, inner and outer, which contain an electrolyte composed of sulfuric acid and potassium bromide. The gas inlet tube terminates in a fritted glass dispersion bubbler under the surface of the liquid in the inner compartment. Since this section is open at both top and bottom, the bubbling action of the entering sample gas acts as an air lift pump and causes the solution to circulate from the inner to the outer compartment. As solution flows out of the compartment, it passes through a wood-charcoal filter which removes any adsorbed titer, and protects the electrolyte in the outer compartment against accumulation of reaction products.

The inner compartment also contains a sensor electrode and a (bromine) generator electrode, parts of 2 circuits in a direct current amplifier system. As oxidizable sulfur compounds enter the cell, they react with the bromine present and cause an unbalance in the bromine sensor elements which, in turn, affects the current output of the amplifier system. To correct this situation, the amplifier system then supplies additional current to the electrolysis electrodes in order to produce enough additional bromine to meet the demands of the oxidation-reduction reaction, as well as maintain the desired residual bromine concentration corresponding to the set balancing voltage.

This bromine generating circuit consists of a cathode in the outer compartment and an *anode* in the inner compartment, which receive their current input from the electronic amplifier circuit. Bromine is thus generated at the *anode* and is available to react with oxidizable materials in the inlet gas stream. Hydrogen is evolved at the electrode in the outer compartment and is swept out of the cell with the air stream.

The bromine concentration sensor-system consists of a bromine-sensitive

* Presented at the 49th Annual Meeting of the Air Pollution Control Association held at Buffalo, N. Y., May 20-24, 1956.

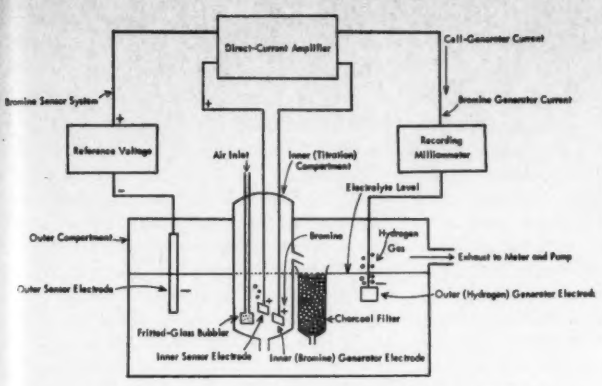

Fig. 1. Titration Cell and Amplifier System

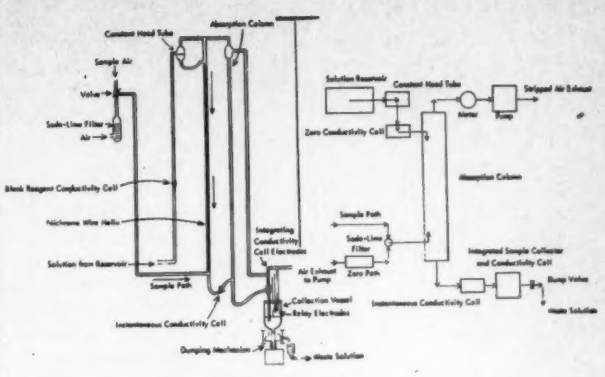

Fig. 2. Autometer.

electrode in the inner compartment and a calomel half cell reference electrode in the outer compartment. In this circuit, also, there is a reference voltage (battery source) used to oppose the voltage between the bromine-sensitive electrode and the calomel reference electrode so that a balance may be achieved. This balance is equivalent to the zero adjustment, and is accomplished by drawing air through a charcoal, soda-lime filter into the inner cell while adjusting the voltage to a point at which the current in the 2 circuits is just equal, at some desired level of bromine concentration. The zero adjustment, normally, is set for a very low bromine level—just enough to equalize the rate at which bromine is removed from the cell by the purified air passing through. Thus, the current supplied to the electrolysis portion of the apparatus by the amplifier at the zero adjustment is just enough to maintain the bromine concentration at this low level. The current through the amplifier system is measured continuously by a recording milliammeter, thereby providing a graphical record of the zero level and of the concentration of oxidizable constituents of the gas stream. Unfortunately, what is recorded is the net titration level, with actual concentrations being obtained only by multiplying this value by a calibration factor, which must be determined separately for sulfur dioxide and any other constituents to be measured.

The Autometer

The operation of the Autometer which was developed by Dr. Moyer D. Thomas[1] for the continuous measurement of sulfur dioxide is, perhaps, more familiar. (Fig. 2) Air is drawn continuously at about 20 ft.³/hr. upwards through an absorption tube and countercurrent to the continuous flow of absorbing solution at the rate of 200 ml./hr. The absorbing liquid consists of an aqueous solution of hydrogen peroxide (3×10^{-3} molar), sulfuric acid (5×10^{-5} normal) and 2 mg./l. of fungicide *Dowicide B*. The absorption column, for its full length, contains a nichrome wire helix to prevent bubbling, and to insure uniform wetting of the walls of the tube and good admixture between the liquid and gas phases.

Before the absorbing solution enters the column, its electrical conductivity is measured as it passes through the first conductivity cell. As the gas to be sampled passes through the absorption column, material such as sulfur dioxide is absorbed and oxidized simultaneously. This process changes the conductivity of the solution, which change is, in turn, measured by the second conductivity cell. Any increase is directly proportional to the amount of sulfur dioxide absorbed and will be recorded continuously as concentration of sulfur dioxide (ppm. or other suitable units). The continuous portion of the cycle normally continues for 27 min. during which the absorbing solution collects in a vessel containing electrodes which activate an electronic relay, and the electrodes for the third conductivity cell. When 100 ml. have collected, the liquid level contacts the relay electrodes, which start the program timer. This switches the reading from the continuous to the integrating conductivity cell for a 1.5 min. period, switches to the zero, or reagent blank conductivity cell for a 1.5 min. period, simultaneously dumps the solution, and switches back to the continuous conductivity cell for another 27 min. and another complete cycle. Thus the Autometer provides a continuous and instantaneous measure of the sulfur dioxide concentration of the air being sampled, an integrated or average measure every half hour, and an automatic check on its reagent blank reading every half hour. A manual zero check is made when the instrument is serviced by turning a 3-way valve to divert the path of the air stream through a soda-lime filter before it enters the absorption column. The filter removes acid gases from the air stream and permits measurement of the conductivity of the absorption solution alone plus any effect from the passage of filtered air. Any change in the zero settings may be noted, and appropriate compensations made, both in reading the concentration of sulfur dioxide when the data are reduced, and in making adjustments when the machine is serviced. In actual practice, it is possible to balance only 2 of the 3 conductivity cells against each other. Therefore, either the integrated reading or the blank cell reading must be only approximate, depending upon which cell is not brought into balance. Normally, it is better to permit the integrated reading to be less accurate.

For accurate operation, it is essential that the absorption column and conductivity cells be enclosed in an insulated compartment thermostatically maintained at 120° ± 2°F. This will minimize error due to ambient temperature variation since a change of 2°F. will alter the conductivity of a strong electrolyte (such as sulfuric acid) by approximately 2%. In some cases, 110°F. may be adequate, but the temperature at which the instrument is maintained should be a few degrees higher than the maximum ambient temperature expected at the location in which the machine is to be operated.

Interferences, Advantages and Disadvantages for Each Instrument

As is the case with quite a number of automatic air sampling devices, both the Titrilog and Autometer are subject to certain interferences. The Titrilog will measure and record as sulfur dioxide other oxidizable sulfur compounds such as hydrogen sulfide, mercaptans, and

[1] M. D. Thomas, J. O. Ivie and T. C. Fitt. *Ind. Eng. Chem., Anal. Ed.*, **18**, 383 (1946).

organic sulfides. This can be advantageous in using the instrument to measure total sulfur, however, as in fuel gases and refinery products. There has been developed, also, a series of filters for the selective absorption of certain of these sulfur compounds, which should make it possible to determine any one of them, independently from the others. Little information is available as yet regarding the use of these filters in actual field sampling, but it seems probable that their most effective employment would be in sampling concentration ranges above 1 ppm. Interference, as evidenced by low results, may also be encountered when the gas stream contains nitrogen dioxide or chlorine.

Some of the principal advantages in using the Titrilog include the ease of preparation and the stability of the solutions and reagents; the ruggedness of the instrument and its ability to operate with infrequent servicing (sometimes as little as once a month except for chart maintenance); its sensitivity (as low as 0.1 ppm. and possibly 0.05 ppm.); its 30 sec., 90% response to a change in sample concentration; and especially, its availability as a portable model without sacrifice of durability or sensitivity. The latter is perhaps the most significant advantage of the Titrilog since it makes available an easily installed and operated, automatic instrument for short period sampling such as might be needed in rapid field surveys, or even for emergencies, such as monitoring gas concentrations when accidental leakage occurs.

There are also, of course, some disadvantages, a few of which may even seem to contradict what has just been said. Some users have felt that in continuous operation, drifting of the zero point and loss of liquid from the reaction cell requires more or less constant attention rather than the infrequent maintenance previously mentioned, and that frequent calibration has also been necessary (in portable use, as often as once a week). Since the sensitivity of the instrument is not the same for all of the compounds it can be used to measure, separate calibrations are necessary for each. Concentrations are not quickly available in ppm. since the only recorded value is net titration level which must be multiplied by a calibration factor to convert to concentration units. In air sampling use, there is an additional disadvantage in that only the instantaneous pollution level is measured so that to obtain accurate determinations of average concentration, the area under the recorded curve must be planimetered.

The chemical interferences which can affect the results obtained using the Autometer include any gas, aerosol or dust, soluble in the absorbing solution, which will change its electrolytic conductivity. Any increase would be recorded as ppm. sulfur dioxide; any decrease would either counteract some of the error introduced by other substances, or cause the apparent sulfur dioxide value to be lower than the actual concentration. In practice, interference from aerosols is minimized by maintaining the flow rates at a point which will cause particulate matter to channel through the absorption column without lowering the degree to which the solution retains sulfur dioxide. In locations where sulfur dioxide is normally present in considerable excess of potential interfering substances, they should present no serious problem. Carbon dioxide need not be considered a serious interference because it is not readily absorbed and because it forms a weak electrolyte which has little effect on the solution conductivity. Hydrogen sulfide might present a more serious problem under certain conditions but, at the Autometer locations thus far maintained in the Los Angeles Basin, its concentration has been low enough to prevent this occurrence. Nitrogen dioxide has not been found to be a serious interference, presumably because the contact time between the air sample and the solution is not sufficient for its absorption.

As pointed out earlier, it is essential that the conductivity of the solution be measured, each time, at very nearly the same temperature. In the Los Angeles area, this condition is often difficult to maintain because of the considerable diurnal temperature variation. This is especially true when the Autometer is installed in a poorly insulated shelter. It is possible, for instance, for a difference of 80°F. to exist between the temperature of the reagent in the storage bottle and the temperature in the measuring compartment. It is, thus, virtually impossible to bring the solution to proper temperature before it enters the absorption tube. This, in turn, accentuates the problem of bubble formation at this point, and their resultant accumulation in the conductivity cells and the collection vessel. Keeping the glassware clean helps to correct the problem, and installation in a heated, well-insulated building can practically eliminate it. Better temperature control could also be achieved by the addition of individual constant temperature enclosures for the conductivity cells instead of depending solely on thermostatic control of the temperature of the whole compartment.

Among the principal advantages of the Autometer are its range of 0-5 ppm. (or 2.5 to 22.5, through a minor change in its electrical system), and its sensitivity, which is better than 0.05 ppm. In addition, concentrations are recorded directly in ppm., and, if the integrating model is used, average values are as readily available as instantaneous values. In these respects, for routine air monitoring, it is preferable to the Titrilog. Its response time, 80% in about 1 min., is not quite so rapid as that of the Titrilog, but is satisfactory for most purposes. Reproducibility of results for both instruments in the range below 5 ppm. is about the same, ± 0.1 ppm.

The Autometer requires more frequent servicing in routine use than does the Titrilog, since fresh solution (a total of 9 gal.) must be supplied at least once a week. Some users even recommend a daily check on its operation for best performance. The absorbing solution is easy to prepare and is sufficiently stable for normal use. Routine servicing, including minor adjustments and repairs, can usually be handled by non-technical personnel by following instructions in the manufacturer's manual. The most serious difficulty which is likely to be encountered is flooding of the absorption column. This can be caused by incorrect solution or air flow rates, dirty glassware, or a combination of the two. The first situation can be remedied by careful adjustment of the flow rates; the second, by washing the column with ethyl or isopropyl alcohol, followed by distilled water, or by using chromic acid, alcoholic potassium hydroxide, or other laboratory glassware cleaning solution, followed by successive rinsing with distilled water, alcohol, and distilled water. The electrodes in the conductivity cells must also be cleaned periodically to avoid error from this source, and must be platinized, when necessary, with platinum black. For best results, each instrument should be calibrated in field use, with acid of known strength or a mixture of air and sulfur dioxide of known concentration.

The Autometer serves best in a permanent location, though it is not so large or heavy that it cannot be moved occasionally. It can also be mounted in a well insulated truck, and so achieve some portability, though even this usage would be limited. The instrument requires a little more installation than the Titrilog since facilities for draining the waste solution should be provided. Both instruments operate on 60 cycle, 115 volt current, but the Autometer requires about 400 watts, while the Titrilog requires only 150 watts.

The Autometer is available both in an integrating or non-integrating model with the same range and sensitivity. It is preferable for air sampling work, since the Titrilog, of course, records only instantaneous concentrations. The District has always used the integrating model, but occasionally, some difficulty has been encountered with erratic operation of the dumping mechanism. Since this is the only check on the solution flow-rate, its faulty operation can cause rather serious errors. For this reason, much consideration has been given to the possibility of incorporating into the sampling system, a rotameter for the measurement of solution flow-rates, and even to elimination of the integrating features if the difficulty cannot be remedied.

Uses of Both Instruments

Both the Titrilog and the Autometer can be utilized satisfactorily for the continuous automatic measurement of sulfur dioxide. For routine measurement of low concentrations of sulfur dioxide, as required in aerometric surveys and other routine air monitoring where a relatively permanent installation will be used, the Autometer seems better suited than the Titrilog. In fact, the Autometer has so far been used almost exclusively for sampling of this type, which may even include routine monitoring of the sulfur dioxide concentration within an industrial plant or near a particular source, or the survey of sulfur dioxide concentration at several points in an area where a study of the effect and control of air pollution is in progress.

The Titrilog, on the other hand, lends itself best to more specialized uses because of its versatility and portability. The stationary model of the Titrilog can be used most effectively where it is necessary to measure total sulfur content of the material to be sampled. This makes it especially useful in maintaining a routine check on the sulfur content of odorized gases such as natural or other fuel gas, on the corrosive sulfur content of natural gasoline, on the efficiency of certain equipment for removal of hydrogen sulfide or other sulfur compounds, and other similar uses. The instrument, through the use of special absorption filters, can even be set to monitor the concentrations of several sulfur compounds in a continuous cycle. For example, measurements by difference, might be made routinely several times per hour, of total sulfur, hydrogen sulfide and mercaptans, by successive absorption through suitable filters. It is even possible through other modifications, to use the Titrilog to measure a particular sulfur compound, or total sulfur, in several different sample streams in repetitive sequence.

The portable Titrilog offers certain additional advantages for special situations and has been used in sampling aloft by helicopter as well as for short duration or spot sampling in industrial plants and in the field. Personnel of the Tennessee Valley Authority[2] have adapted such a unit for installation in a standard passenger automobile and for one-man operation while the car is in motion. Mounted in an automobile, it could be utilized in certain emergencies to monitor the concentration of sulfur-containing gases which might be put into the air accidentally, as from a gas leak, pipe line break, or equipment breakdown.

The portable model is contained in 3 separate carrying cases, no unit of which is larger than 11 in. wide, 22 in. long, and 12 in. high, or weighs more than 50 lb. Installation involves simple connection to a suitable power source, and the instrument can be operated on certain types of portable generators or on a 12-volt automotive electrical system with certain modifications. Reliable determinations can be made easily and quickly even by non-technical personnel with a minimum of instruction. In this phase of sampling, only the Titrilog has thus far been successfully employed.

Neither instrument is likely to be of value in stack sampling work. The Autometer could not be used at all because of its size and weight, and because chemical interferences would probably be present in considerable quantity. Conceivably, however impractically, the portable Titrilog might be adapted for stack sampling, but only in situations where the concentration of sulfur compounds did not exceed 30 ppm., where the stack gases could be cooled to normal air temperatures before entering the measuring compartment, and where a sufficiently large sampling platform was available to accommodate the instrument. Normally, conventional methods of sampling would be far preferable.

Conclusions

It appears that either principle is adaptable to the measurement of sulfur dioxide, but that careful selection is necessary to insure using the best instrument for each sampling situation. Each has advantages and limitations which must be understood. For a permanent or semi-permanent installation where sulfur dioxide measurement is the principal or only purpose, the Autometer or the Titrilog, will be satisfactory. The Autometer, however, will probably be simpler and less expensive to operate for this kind of sampling and will be subject to fewer interferences than the Titrilog, if properly installed and maintained. In situations which require determinations of other sulfur compounds, or where portability is an essential or even desirable feature, the Titrilog should be selected. There are, of course, other instruments or sampling methods which could be used successfully for some of these purposes, but they have not been considered in this discussion.

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[2] S. B. Carpenter and R. E. Sparkman. *J. of APCA* 5, 195 (Feb. 1956).

The Development of a Forecasting Service for Use in Air Pollution Control*

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In May 1949, the Tennessee Valley Authority began construction of the first of its major steam-electric plants to meet increased demands for electric power in the postwar period. Since then, 6 additional plants have been authorized by Congress.

Construction of the Kingston power plant, located on Watts Bar Lake, 2 miles north of Kingston, Tenn., was started April 30, 1951. The first of 9 units was placed in commercial operation on Feb. 8, 1954, and the ninth unit went into commercial operation in December 1955. The Kingston power plant is believed to be the world's largest, with a total capability of 1,600,000 kw.[1]

Like all of TVA's large steam plants, the Kingston power plant is coal-fired. It is estimated that the Kingston plant alone will use 4,300,000 tons annually at 80% load factor. In view of the quantity of waste gases to be disposed of from this and other plants, TVA has included air pollution control in design and operation plans.

To provide adequate dispersion, waste gases are customarily discharged into the atmosphere through high stacks at high speeds. In the absence of local effects resulting in distortion of the wind and temperature fields around the plant building and stacks, these waste gases are dispersed by natural atmospheric turbulence and changes in the direction of wind flow. At TVA power plants, a program of air pollution studies is being conducted which serves to evaluate effectiveness and to identify any need for additional controls.[2,3]

Experience in other areas has taught that occasionally meteorological conditions develop which inhibit dispersion of airborne wastes over a period of several days, and which lead to abnormally high concentration of waste gases at ground level. Such episodes occurred at Donora, Pa., Oct.27-31, 1948,[4] Greater London, Dec. 5-9, 1952,[5] and near Liege, Belgium, Dec. 1-5, 1930.[6] Such prolonged periods of air stagnation are rare.

The Kingston power plant is located on the floor of an Appalachian valley several miles east of historic Walden's Ridge. Local topography is characterized by many parallel ridges oriented northeast-southwest, and rising from 400 to 1000 ft. above the valley floor. Numerous traverse notches cut the ridges almost to floor elevation. Such topographical features in a zone of slowly-moving anticyclones call for consideration of the possibility of prolonged air stagnation.

Effects of Weather on Dispersion of Stack Gases

Three local weather elements may be considered as the primary weather factors which determine the concentration and effect of airborne wastes in the lower atmosphere. These are: (1) wind speed, direction, and turbulence, both at the surface and aloft; (2) temperature change with height, or more generally, the resistance to vertical motion of the lower layers of air; and (3) humidity, including condensation forms, particularly fog. These 3 factors are, of course, not mutually exclusive. Investigations of known occurrences have identified all 3 of these elements are contributing to the accumulation of abnormally high concentrations of air pollution. The meteorologist also recognizes that local topography may serve to influence the contribution of any of the 3 factors to the total degree of air pollution.

A brief discussion of the role of each of the 3 meteorological elements at Kingston follows: Emphasis is given to the operation of each element during periods of stagnant air.

Wind

The role of the wind in effecting dilatation of the waste gas downwind of the stack is obvious and is directly proportional to the wind speed. Not so obvious is the role of the wind speed (1) in affecting the virtual stack height, *i.e.*, the level at which the buoyancy rise of the waste gases becomes negligible, and (2) in generating the complicated system of eddies whereby the waste gases are dispersed horizontally and, not necessarily to the same extent, vertically. In the first case, the effective stack height decreases rapidly with increase of wind speed, while at very low wind speeds the stack plume rises nearly vertically until the buoyancy forces have become negligible. In the second case, the wind force (variable with height) influenced by and also influencing the thermal stratification of the air (also variable with height) can generate a multifarious variety of eddy sizes and distribution, the more so in the presence of a heterogeneous underlying surface.

Wind direction also must be considered. As long as the term *downwind* applies, *i.e.*, as long as the wind direction remains fairly steady and the wind speed does not fall to zero, the waste gases from *a single source* will be dispersed in a sector of some size downwind. Conversely, the complement of this sector will be free of any waste gases. But the wind direction in actuality shifts with the passage of weather systems identifiable on the surface weather map, and even from hour to hour, especially with mild pressure gradients in topography, such as that at Kingston. Ordinarily,

(1) Tennessee Valley Authority Rept. of the Chief Engineer, Fiscal Year 1954, Knoxville, Tenn. (Aug. 1954).

(2) Fred W. Thomas. TVA Air Pollution Studies Program. *Air Repair* 4, 59-64 (Aug. 1954).

(3) F. E. Gartrell and S. B. Carpenter. Development of a Technique for Study of Diffusion Patterns by Using Helicopter for Sampling Aloft and Near Ground. *J. Meteorol.* 12, 215-19 (June 1955).

* Presented at the 49th Annual Meeting of the Air Pollution Control Association held at Buffalo, N. Y., May 20-24, 1956.

* Also published in *A. M. A. Arch. Ind. Health* 14, 307-18 (Oct. 1956).

† Previously on special assignment with TVA.

(4) H. H. Schrenk, H. Wexler et al. Air Pollution in Donora, Pa.; Epidemiology of the Unusual Smog Episode of October 1948; Preliminary Report. *Pub. Health Bull.* No. 306 (1949).

(5) Smog. *Quart. J. of the Roy. Meteorol. Soc.* 80, No. 344, 261-78. Includes the following papers with discussions: H. W. L. Absalom. Meteorological Aspects of Smog, pp. 261-6; E. T. Wilkins, Air Pollution Aspects of the London Fog of December 1952, pp. 267-71; N. C. Oswald. Physiological Effects of Smog, pp. 271-2.

(6) J. Firket. Fog Along the Meuse Valley. *Trans. Faraday Soc.* 32, 1192-7 (1936).

shifting winds might be expected to have a beneficial effect, since the lateral dispersal of the waste gases would be thereby enhanced. However, if the wind speed and rate of atmospheric diffusion remain low for an extended period of shifting winds, there would be an accumulation of stack effluent in the vicinity of the plant. When also the distribution in space and the intensity of vertical mixing are such that the ground is fumigated, there would be expected comparatively large ground dosages of the waste gases, if not large concentrations.

Temperature Lapse

The importance of the temperature distribution in the vertical lies in the fact that it largely determines the resistance of the air to vertical displacement. For unsaturated air, the adiabatic lapse rate represents the vertical temperature distribution which neither favors nor inhibits vertical interchange. This lapse rate corresponds to a decrease of 5.5° F. in the air temperature as we go up 1000 ft. On the average, the lapse rate in the atmosphere is more nearly 3.3° F. per 1000 ft. Such a condition is stable for unsaturated air, and vertical interchange of matter requires the expenditure of energy, mostly derived from the wind stream and from solar heating. The smaller the lapse rate, the greater the energy required to effect vertical interchange. A negative lapse rate is known as an inversion. The efficiency of even small inversions in restricting vertical mixing of a smoke layer has been observed many times.

Under a clear sky and with light winds a shallow inversion based at or near the surface is produced nightly. Inversions of this type effectively inhibit vertical diffusion as long as they persist. The greater the vertical extent of an inversion, the greater is the quantity of heat required to break it up. In the more severe cases, diurnal heating is insufficient to cause breakup. If this condition persists for several days, vertical diffusion of waste gases in the area will be inhibited and relatively concentrated volumes of waste gases will appear in the lower layers of the atmosphere.

Relative Humidity and Fog

The role of relative humidity as a weather factor in smog formation is not as direct as that of wind and stability. The humidity of the air in itself probably has little, if any, direct effect upon the degree of concentration of waste gases. The condensation forms which occur under high humidity conditions might, however, have a direct effect. If the condensation form precipitates as rain or drizzle, the effect may be beneficial to the extent that absorbed gases or included particles are rained out. It is conceivable that descending air currents accompanying heavy precipitation will carry the plume of waste gases to the vicinity of the ground *prematurely, i.e.*, before natural diffusion has operated long enough.

If the condensation form remains suspended as fog, no beneficial effects are expected. The primary contribution of fog to the degree of concentration is that the presence of fog limits and may interrupt the normal enhancement of vertical diffusion by solar heating during the daytime.

TABLE I

Characteristic Weather Elements at Kingston, Tenn. During Brief Periods of Air Stagnation

Weather Element	Extremes	Most Frequent
Hourly average wind speed		
low station	0 — 11 mph.	1 mph. (6); 1 and 2 mph. (11)
high station	0 — 4 mph.	3 mph. (4)
Hourly average range of speed		
low station	0 — 3 mph.	2 mph. (12)
high station	0 — 2 mph.	2 mph. (7)
Prevailing direction		
low station	—	ESE and SW (5 each; N through ESE (13)
high station	—	S (3); ENE through ESE (5)
Hourly range of direction,		
low station	15 — 75°	40 — 55° (9)
high station	10 — 70°	40 — 55° (3)
Hourly maximum range of direction,		
low station	60 — 360°	360° (11); 60-175° (8)
high station	25 — 360°	360° (3)
Gustiness types[1]		
low station	—	B_2 (11)
high station	—	B_2 (4)
Lapse at mid-hour		
low station	—5.0 to +5.5° F	broad distribution centered on interval —0.5 to +1.5° F.

Local Weather During Short Periods of Atmospheric Stagnation

A survey of the period June 29, 1954, when the fifth of 6 Autometers was installed near Kingston, Tenn., to Oct. 26, 1954, reveals that some sulphur dioxide was registered simultaneously in all directions around the plant on 7 different occasions. The simultaneous recording of sulphur dioxide at widely separated points about the source must be considered evidence that local weather conditions were favorable to accumulation of waste gases in the general neighborhood of the plant. The meteorological conditions prevalent at these times can be taken as an indication of the elements which contribute to such accumulations.

The wind and lapse measurements summarized below cover the period from at least 1 hr. before to at least 1 hr. after each of the 7 occurrences. Twenty hr. of data at the *low station* and 8 hr. of data at the *high station* are considered. The *high station* was installed about 1 month before the end of the period of survey. The table below lists essential data concerning the *high* and *low* stations, while Table I lists extreme and most frequent values of certain weather elements associated with the simultaneous registrations.

	High Station	Low Station
Ground Elevation (ft. msl.)	1134	859
Anemometer Height (ft. msl.)	1320	1009
Height Interval of Lapse Measurement (ft.)		146

It may be observed in Table I that the local weather conditions at Kingston characteristic of these periods of atmospheric stagnation include the following:

a. Very low values of hourly average wind speed.

b. A tendency toward prevailing wind directions from the north through east to southwest, in agreement with the observed passage of the majority of the high centers north of Kingston.

c. Generally moderate values of average range of wind direction over the hr., but frequently large values of the maximum range; in about half of the cases the maximum range attained 360°.

d. A wide range of values of temperature lapse in the lowest 145

[1] Maynard E. Smith. The Forecasting of Micrometeorological Variables. *Meteorol. Monographs* 1, No. 4, 50-5 (1951).

ft. more or less centered on the adiabatic rate.

Significantly, 6 of the 7 instances of simultaneous registration of sulphur dioxide at 5 or more Autometers occurred between 9:30 a.m. and 4:00 p.m. Two of the daytime instances persisted each for 2 hr., while the remaining 5 lasted only for half an hour. It is conjectured that in these brief periods of atmospheric stagnation, the waste gases diffusing at a slow rate over a widespread area aloft were periodically brought to the ground in occasional large scale eddies of thermal origin. Similar action is considered not unlikely in the case of prolonged periods of stagnation. It, therefore, must be considered as a possibility that the complete or partial dissolution of a stagnant condition may represent a phase during which time relatively concentrated volumes of waste gases aloft can be brought near the ground.

Local Weather During Stagnation Periods in Other Areas

Detailed investigations of the weather which attended smog concentrations in other areas reveal that all of the factors outlined above were operative for several days[4,5]. The simultaneous occurrence of light, shifting winds, great stability, and fog for brief periods is not a particularly rare phenomenon, especially in hilly country. But experience has suggested that the condition must persist for several days before abnormal concentrations occur. The requirement of prolonged simultaneous occurrence of all 3 weather factors make the event a rare and exceptional meteorological phenomenon.

The Meteorological Stagnation Model

The polar anticyclone undergoing transformation to the deep warm-type anticyclone appears to be the meteorological model most likely to produce the prolonged stagnant conditions required for abnormally large waste gas concentrations. All occurrences mentioned earlier were associated with this meteorological model. However, a forecasting service designed to enable industry to prevent abnormal concentrations must not limit itself to the prediction of the development of quasi-stagnant anticyclones. It is possible that some other meteorological model also can produce the stagnation requirements, and, consequently, the forecasting service must be directed toward the identification and prediction of required local weather elements, rather than a particular model.

Within the limitations described above, the basis for the prediction of prolonged stagnant periods is the large-scale general circulation. Such periods of stagnation in the East Tennessee Area are characterized by the presence of an intense low-pressure system over the western or central Atlantic at middle latitudes. The eastward movement of the system must be blocked in turn by a very extensive anticyclone to the east and/or north. This type of *blocking* high precedes the development of a stagnant anticyclone over the eastern United States by several days.

Stagnation Warning Service

The stagnation forecasts provided to TVA by the Weather Bureau Office at Knoxville bear 3 designations:

1. Stagnation trend advisories.
2. Stagnation alerts, and
3. Extreme local stagnation warnings

The stagnation trend advisories are issued twice weekly during the fall months, and intermittently as required during the balance of the year. These advisories consist of a brief appraisal of the general circulation over the Northern Hemisphere (limited to available data) in terms of its tendency to become more or less stagnant over the Southern Appalachian Region, and particularly the Tennessee Valley. A trend toward greater stagnation is designated as *positive* and a trend away as *negative*. The arrangement for regular advisory service during the fall months was made in recognition of the fact that stagnation occurs in this area most frequently in the fall. These advisories are used for planning purposes by the plant operator and by an air pollution control team. Advisories are not intended to be used as the basis for initiation of modified plant operation; rather, the receipt of a *positive* trend forecast constitutes notice to prepare for imminent control action, although such action may not prove necessary.

Stagnation alerts are issued whenever the general circulation indicates the development of a 48-hr. or longer period of local stagnation over the Southern Appalachian Region. The alert is used by TVA as a basis for modifying plant operation in the interest of pollution control. Meteorological elements at the plant site which have been identified as essential to the development of high local concentrations are thereafter reported at regular intervals to the forecast office for evaluation.

Both the stagnation trend advisories and stagnation alerts must be based upon the general circulation over the Northern Hemisphere. Since practical considerations necessarily limit the volume of data and areal coverage available at field stations, primary dependence in making these forecasts must be placed upon the data and advices issued by the Extended Forecast Section, the National Weather Analysis Center, and the District Forecast Office. Since both the stagnation trend advice and the stagnation alert refer primarily to the large-scale features of the general circulation, the information available from these sources is well adapted to the need, and the lack of extensive detailed large-scale data does not represent a handicap.

A stagnation alert is not issued in anticipation of a stagnating anticyclone over the Eastern United States as soon as a *blocking* high is established in the central or eastern Atlantic. Since several days of coincident unfavorable weather factors appear to be required for the accumulation of dangerous amounts of pollutants, the alert warning is timed after these general circulation requirements have been fulfilled and a polar anticyclone has begun to settle over the Appalachians. After the issuance of the alert, sufficient time remains for TVA to take preventive action.

After a stagnation alert has been issued, it is maintained as long as the high pressure center remains over the area. If the threat is not realized, a definite termination message is delivered to TVA, however, if local observations at the plant site indicate that all of the criteria described in the following section are fulfilled and will continue for 24 hr. or more, an extreme local stagnation warning is given. This warning constitutes notice that all local meteorological elements considered necessary to the accumulation of abnormal concentrations of pollutants are prevalent and are expected to persist. These alerts are the basis for beginning modified plant operation in the interest of pollution control.

Extreme Local Stagnation Warning Meteorological Criteria

Criteria for the issuance of an *extreme local stagnation warning* have been patterned after the recommendation of Willett in his report to the Industrial Hygiene Foundation on the Donora episode.[6]

During that episode, wind speeds remained under 7 miles/hr. from the surface up to 5000 ft. msl. for a period of 3 consecutive days. On the basis of the limited data available for the Kingston

[4] See Footnote 4, page 228.

[5] See Footnote 5, page 228.

[6] H. C. Willet. The Meteorological Conditions Related to the Occurrence of Smog at Donora, Pa. Dept. of Meteorology, Mass. Inst. of Tech., Cambridge, Mass., for the Ind. Hyg. Fdn., Inc., Pittsburgh, Pa. (1949) Unpublished.

site, a prolonged period of wind speeds of less than 10 miles/hr. at the surface and aloft has been selected as the tentative criterion with regard to wind. It is hoped that experience will justify a lower value, and thereby decrease the frequency of warnings and preventive operations.

In their analysis of the meteorology of abnormal concentrations, both Willett[8] and Fletcher[9] emphasize the temperature difference between a low and a high elevation as an index of the low level stability. Since the maximum temperature usually occurs during the period of maximum diurnal heating and since this is the time when the lower atmosphere is most likely to become unstable and provide the most effective vertical mixing, a negative temperature difference is considered highly significant evidence of low level stability.

No upper air soundings are available at Kingston and temperature lapse measurements are made over a height interval (146 ft.) too short for effective utilization as a criterion of stability in a deep layer. Fortunately, a relation of altitudes similar to that reported by Willett prevails for the temperature measurements available at Kingston and at Knoxville airport. The elevation of the latter is approximately 250 ft. higher than Kingston. The average temperature difference, (Kingston maximum temperature) minus (Knoxville airport maximum temperature), for the fall months of 1953 and 1954 was found to be —0.27°F. During this period there were 4 runs of negative temperature difference of 2°F. or more for 3 or more consecutive days. On the basis of the limited data available at Kingston, a negative difference of temperature maxima exceeding 1°F. has been selected as the tentative criterion with regard to stability.

Willett's study of the stagnation period of Oct. 27-30, 1948, reveals that fog persisted in the valley beyond the noon observation each day during the period. Persistence of fog beyond the noon hour has been selected conditionally as the tentative criterion with regard to fog. Since the primary meteorological effect of the fog is attenuation of solar heating and hence daytime turbulence, if the wind and stability criteria are fulfilled the forecaster may elect to issue an extreme stagnation warning, even though fog breaks up at an earlier hour.

[8] See Footnote 8, page 230.

[9] Robert D. Fletcher. The Donora Smog Disaster—A Problem in Atmospheric Pollution. *Weatherwise* 2, No. 3, 56-60 (June 1949).

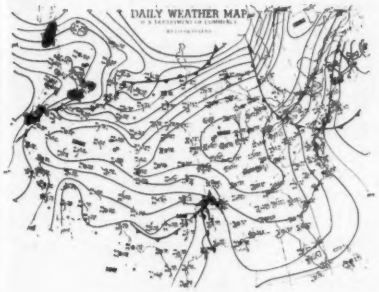

Fig. 1A. Map for 1:30 a. m. EST 10-22-54

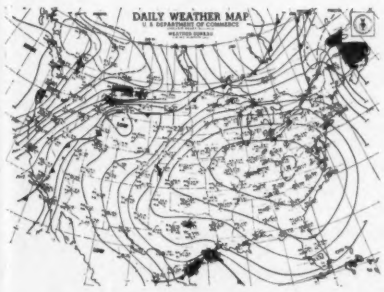

Fig. 1B. Map for 1:30 a. m. EST. 10-23-54

TABLE II

Total number of 3-day Anticyclones over the Tennessee Valley, January 1899 through June 1939

Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Total
4	0	1	2	2	3	4	4	9	20	9	7	65

Frequency of Stagnation Alert Periods

To formulate an estimate of the expected frequency of prolonged stagnation periods over the Tennessee Valley, a survey was made of the regional weather from January 1899 through June 1939. In this survey all anticyclones which persisted 3 days or longer and which covered the Tennessee Valley within the first or second isobar were counted, using the Historical Weather Maps for the Northern Hemisphere. Sixty-five cases were found during the period of record surveyed. Table II shows the distribution of the 65 cases by months.

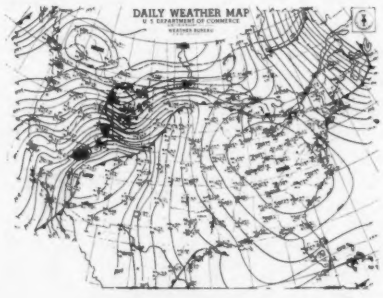

Fig. 1C. Map for 1:30 a. m. EST. 10-24-54

Only a small fraction of these cases could have resulted in severe smog conditions, with appropriate wind, stability, and daily fogs. However, by definition each of these 65 occurrences would have required a stagnation alert. In addition, it is reasonable to assume that under the normal uncertainties necessarily associated with any forecast, there would be an additional number of alerts which would not be verified. A survey of the synoptic charts and other data regularly received at the Knoxville Weather Bureau Office reveals that for the months of August through November 1952 and 1953, the threat of a stagnating anticyclone arose 7 times but only one of these threats developed sufficiently to fulfill the requirements for issuance of an alert.

On the basis of these 2 surveys, it appears reasonable to assume that the average frequency of stagnation alerts over a long period of operation would be between 2 and 3 times a year. Since a general circulation pattern of the type required for stagnation over the eastern United States once established tends to perpetuate itself, it is also quite probable that the occurrences in any 1 yr. might exceed this average considerably. During the 40 yr. period surveyed, the highest frequency for a single season was 5, and for any single month, 3. During the 40-yr. period, the assumed average of 3/yr. was exceeded 5 times. Three occurrences during any continuous 30-day period occurred but once.

Case Study

Late in October 1954, the first warning under this service was given to TVA. A brief case history of this stagnation

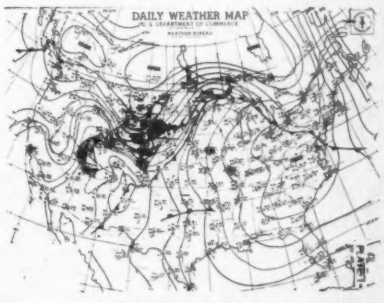

Fig. 1D. Map for 1:30 a. m. EST. 10-25-54

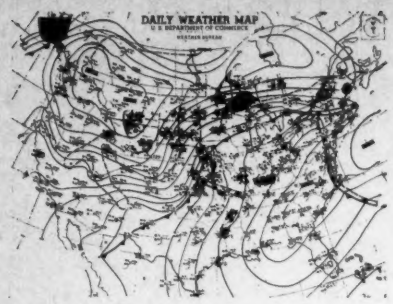

Fig. 2. Map for 1:30 a. m. EST. 10-26-54

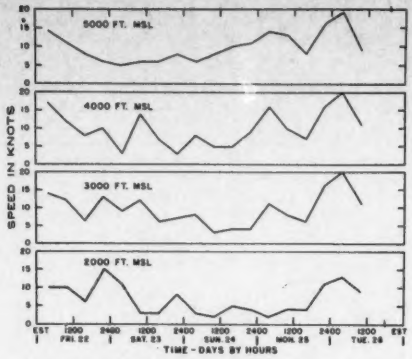

Fig. 3. Winds aloft, Knoxville weather bureau airport station. October 1954.

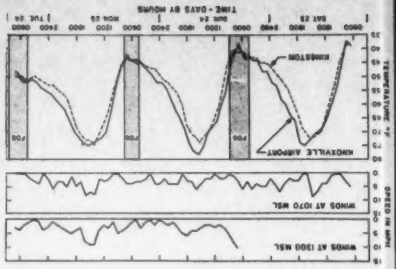

Fig. 4. Hourly winds at Kingston and hourly temperatures at Knoxville airport and at Kingston, and fog duration at Kingston. October 1954.

period follows.

On Tuesday, October 19, the advices received in the local field office from the Extended Forecast Section, the National Weather Analysis Center, and the District Forecast Office, indicated that a *blocking high* was prevalent over Europe and the eastern Atlantic, with indications of the development of a deep low pressure system over the Middle Atlantic Ocean and a general deceleration of the easterly movement of systems during the next 5 days. On the basis of this information, the semi-weekly stagnation trend advisory, which was transmitted to TVA on this day indicated that the stagnation trend was expected to become positive that night and remain positive until Monday or Tuesday.

By Saturday morning, the anticyclone had settled over Tennessee and North Carolina. All available meteorological data gave little support to further southeastward movement of the center. Accordingly, the first stagnation alert was issued this morning. The alert remained in force until 0900 EST, Tuesday, October 26, at which time it was terminated. Throughout the alert period local observations were made at the plant site on an hourly basis and transmitted to the Weather Bureau Office for evaluation. Fig. 1 and 2 show the daily position of the anticyclone over the Southern Appalachian Region during this period. Fig. 3 and 4 present a graphic record of the temperatures and wind velocities observed at Kingston and at the Knoxville airport, together with the duration of fog at Kingston during the period.

The period of greatest stability occurred on Sunday, Oct. 24, 1954, when the maximum temperature difference between Kingston and Knoxville airport showed a negative departure of 4°F. Uniformly low wind speed at all levels up to 5000 ft. msl. also prevailed and the heaviest, most persistent fog was observed on this day. Simultaneous registrations of sulphur dioxide occurred at all 6 Autometers on this day, persisting from 2:00 to 4:00 p.m. Of special interest was the behavior of the smoke plume. Early in the afternoon, portions of the plume were observed to travel away from the rising core at 3 different levels in 3 different directions. Similar behavior of the plume had also been observed on October 5 when simultaneous registrations of sulphur dioxide occurred. It is possible that this behavior of the plume may become a valuable on-the-scene method of evaluating the degree of stability at the plant.

Upon receipt of the stagnation alert on Saturday morning, October 23, the plant personnel took steps immediately to modify plant operations according to pre-arranged plan. From monitoring instruments and special sampling it was determined that satisfactory control was achieved.

Conclusion

The forecasting service as described above leads to a particular control action. Since preventive measures may take time to set into operation and can be expensive, still another reason appears for developing more accurate medium-and long-range forecasting methods. In the present case, recognition of potential air stagnation is not a severe forecasting problem, but the number of false alarms must be kept small, while insuring that notice is given of all genuine periods of stagnation.

A study of weather situations in the eastern United States which favor air stagnation has already appeared.[4] It would be well to extend these considerations to other regions, seeking other meteorological models for air stagnation, and taking into account topographical features and land-sea boundaries.

[4] See Footnote 4, page 228.

Local, small-scale weather processes which accompany stagnation of the larger-scale weather patterns also require further attention. The nearly calm, on the average stable, yet restless field of flow which occurs at times in the lower atmosphere is more difficult to quantify than the familiar case of moderate or strong wind, steady in direction. However, qualitative and phenomenological studies can form the beginnings of a challenge to this difficulty.

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The Present Status of Composting and Its Air Pollution Aspects

ROBERT F. McCAULEY
Michigan State University
East Lansing, Mich.

Composting is a process in which waste organic materials are broken down into humus material for use in agriculture, gardening or the improvement of lawns. The process is an entirely natural means for returning organic matter to the soil and is quite comparable with the process by means of which nature may have built the fine, rich black soils common to many regions.

For many years European and Asiatic nations have maintained a keen interest in the composting process because of critical deficiencies in fertilizers and soil conditions. Composting has been carried on in these areas on both an individual and municipal basis and a number of composting organizations have grown up. However, in the United States it has been felt that commercial composting will not be feasible until developments in the process have overcome objectionable features which have been common to most large-scale operations. Interest in composting has, therefore, been restricted in this country to gardeners, *organic cranks* and to a small group of promoters and researchers who have sought to develop the process on a practical scale. Although much credit is due to all these men for their faith in the composting process and for their continued efforts to demonstrate the usefulness of composting for treating organic wastes, numerous abuses have unfortunately arisen which have given composting an unsavory reputation which it has not rightfully deserved.

Many questionable and false claims have been made regarding the value of composting and for proprietary processes involving secret bacteria and untried equipment. Promises of routine large scale odor-free composting in 2 to 4 days or less have been lightly made with resulting disappointments. Almost invariably composting projects promoted upon such basis have failed due largely to lack of technical skill and an almost complete absence of understanding of the biological principles involved.

During recent years a trend toward the development of sounder and more scientific methods of composting has been apparent. Work has been done in New Zealand, the University of California, Michigan State University, the United States Public Health Service and by several interested municipalities. A trend toward organization of commercial composting upon a sounder basis has also been apparent, although ill-advised and unsound attempts at municipal and commercial composting continue. This trend has increased the interest of public health authorities and municipal officials in commercial composting. A discussion of both the present state of the art and of the problems attendent to large scale composting is, therefore, quite in point at this time.

Almost any organic waste material can be broken down into black humus or compost in time. The natural processes of nature are such that these materials are attacked by bacterial organisms and are utilized for food over a variable period of time. Organic materials rich in nitrogen are broken down much more rapidly than nitrogen-deficient substances. If the composting material is turned from time to time to promote the penetration of oxygen into the decaying matter, the breakdown is more rapid than would otherwise be the case.

Under natural conditions of bacterial breakdown humus is produced from waste organic materials such as garbage or agricultural wastes in 6 months to a year. However, it has been observed that if the wastes are finely ground, adjusted to a moisture content to 50 to 60% and piled in windrows 3 or 4 ft. across the base and 3 or 4 ft. high that a rapid rise in temperature will be observed. If the windrow piles are turned at intervals of 1 to 2 days, a pleasant-smelling humus or compost is produced in about 10 days time. During this 10-day period the material will have passed through a low pH or acid stage and have become quite alkaline with a final pH level of about 8.5. A temperature rise to between 50 and 70°C. (120 to 160°F.) will commonly have occurred. Finally, the organic material will have changed into a friable humus bearing little resemblence to the initial solid waste.

The simplicity of this procedure has led many men to attempt large-scale projects. These projects have been upon either a windrow or digester plan. Windrows have been built in all sizes and shapes and with and without devices for ventilation. Windrows have been turned by hand, with windrow turning machines, by tractors with front-end loaders, by bulldozers and by devices borrowed from the mining and construction industry. Raw materials have been garbage, refuse (mixed garbage and trash), trash and sewage sludge, agricultural wastes and manures.

Digesters have varied in size and design, although all have consisted of a device for continuous turning of the composting materials for rapid aerobic digestion. Several attempts have been made to use a *cement kiln* type digester with varying degrees of success, the most important of these devices being the Dano digester used extensively in Denmark. Another composting digester consists of a number of decks with plows fixed upon a central shaft and driven by a central gear arrangement. The plows turn the waste material and move it from deck to deck. In this unit trap doors feed the material from one deck to the next upon a so-called *continuous feed* basis which is claimed to accelerate the digestion process. A somewhat similar, but apparently more effective device consists of a horizontal unit in which material is aerated by rotating forks.

Other composting digesters have been built to drop the composting material from deck to deck by hopper arrangements or to move the material by screws or belts. A number of such devices have been patented and attempts have been made to sell them commercially, usually with slight success.

Most of the devices for composting mentioned above have showed some degree of promise. Early models suffered from inadequate driving power and inadequate grinding facilities. Another serious problem has been the development of adequate methods for feeding and conveying the raw and ground materials. Trash and refuse have posed unique problems because of the necessity of either grinding or removing the metal, glass and tree limbs. Mechanical difficul-

ties and poor organization have been common and failure has often resulted from these causes.

Principles of Composting

The purpose of this paper is to discuss the present status of composting in a general way and to present some of the air-pollution aspects which attend such operation. In order to clarify some of the points which will be made later some further mention of the principles of composting should be made since these principles are not too commonly understood.

Modern composting is an aerobic process in which waste organic materials are ground or shredded and then either piled in windrows or fed into the decks of a digester. In both digester and windrow processes the biological principle is the same. Oxygen from the air penetrates into voids of the material where it dissolves in the liquid moisture films and is carried to aerobic bacterial organisms. The aerobic bacteria are largely responsible for the breakdown of organic material in relatively rapid, that is 5 to 10 day composting.

Since oxygen supply is commonly limited in composting to a level less than the maximum demand rate some part of the breakdown is probably carried on by anaerobic bacteria which do not require oxygen, and in fact, thrive on the absence of oxygen. Probably the heat generated in composting is due to the aerobic or oxygen loving bacteria. Anaerobes living in the centers of the composting particles neither receive nor require oxygen, but probably thrive at the higher temperatures brought about by the activity of the oxygen-demanding aerobes.

Little is actually known regarding the relationship of the various types of bacterial organisms which are present during composting except in a general way. This is because the multiplicity of organisms present makes studies by convential bacteriological methods almost impossible.

However, it may be stated that the bacteria required for successful composting are always present in materials such as raw garbage or other organic wastes.

Because rapid composting is dependent upon a high level of aerobic activity it is necessary in both digester and windrow composting processes that some provision be made for a continuous supply of oxygen for the composting mass. In digester operation, oxygen is supplied by a turning mechanism which stirs the material so that oxygen from the air is made continuously available to the aerobic bacteria. In windrow composting, the material is piled in windrows in such a way as to provide for a large mass of voids. Voids store an initial oxygen supply to encourage the growth of aerobic organisms and serve as channels through which oxygen can pass to continuously replenish the supply for this kind of aerobic biological activity.

The void space in a windrow pile is soon seriously reduced by the natural tendency of the material to settle and compact. For this reason, it is necessary in windrow operation to turn the piles periodically, preferably every day or two. Turning restores void space and also serves to turn the core material of the pile to the outside so that strictly anaerobic conditions are not permitted to develop.

Unless a forced air feed is used for composting, oxygen is continuously supplied to the aerobic bacterial organisms by a process of diffusion due to partial pressure differences between the outside atmosphere and the composting material. In utilizing the waste material as food, the aerobic bacteria use oxygen and produce carbon dioxide and water. The water would soon fill the voids of the material and stop further movement of oxygen into the compost piles if it were not for the heat produced which evaporates moisture, often at about the same rate as it produced. The air voids, therefore, remain open and carbon dioxide diffuses to the outside of the pile into the atmosphere and oxygen diffuses into the pile where it dissolves in the moisture films and thus, becomes available to the aerobic bacteria.

Oxygen cannot diffuse into a composting material at a high enough rate to completely supply the requirements of the aerobic organisms; therefore, growth of the aerobic bacteria is restricted to a degree. Whether such restriction of growth of the aerobes and the attendant increased growth of the anaerobic bacteria is desirable is yet to be determined. Presumably, some restriction of oxygen supply is not serious, since compost piles in which oxygen is unquestionably limited produce good compost in 10 days to 2 weeks.

In all composting, moisture content is critical. High moisture contents results in the voids of the material being filled with water and oxygen transfer is prevented from taking place; low moisture levels arrest biological activity. Moisture content is particularly critical in digester operation, and a level of above 60% often results in anaerobic conditions with resulting foul odors and inefficient digestion. Because of the manner in which windrow piles are built, a somewhat higher level of 65 to 70% moisture can sometimes be maintained without development of undesirable anaerobic conditions. High moisture windrow piles require frequent turning because compaction of the piles reduces void space and produces odors.

In general, for both mechanical composters and for windrows the presence of trash and other coarse material is helpful because of the tendency to provide bulk and to increase free air space.

When a windrow pile is properly constructed, a rapid rise in temperature is always observed. Under satisfactory conditions, a temperature level of 90 to 100°F. is usually noted after 24 hr. and within 2 or 3 days the temperature rises to 150 to 170°F. These temperatures are self-generated by the activity of the bacterial organisms in utilizing the waste organic matter as food. Each aerobic bacterial organism uses oxygen for biochemical combination with the carbon of food material and in the process produces carbon dioxide, water and heat. In a sense, then, the composting process is a slow burning of the material which is being reduced to humus. Normally, about ½ of volatile organic matter is lost to the atmosphere as carbon dioxide and water.

Temperature levels in mechanical composters are similar to those noted in windrow piles. Near the point of raw waste feed, the temperature is commonly in the vicinity of 100°F. and a rise to perhaps 150 or 160°F. is noted toward the middle phase of the process.

Many mechanical digesters are constructed so that material in the various stages of composting is continuously fed and removed from the deck levels or stages. It is believed by a number of people that this process increases the rate of breakdown and that a much higher level of bacterial activity is maintained. Each deck of this kind of mechanical composter is thought to maintain a bacterial flora which is particularly effective for a specific stage of the composting process and it is considered that incoming material serves as food for bacteria which are present in very large numbers. The composting material is continuously removed from each deck or stage of digestion and transferred to a lower stage (or deck) where it serves as food for a new flora or organisms which is capable of carrying the process one step further.

Problems Encountered in Composting Operations

For 2 years, 1953-55 an attempt was

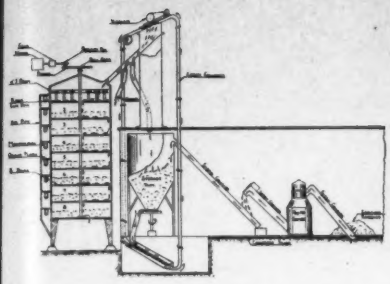

Fig. 1. High rate composting pilot plant. Not to scale. (Michigan State University).

Fig. 2. Two photographs of the compost operation. Experimental digester (1) and gas analysis in windrow pile (2).

made by the Department of Civil Engineering of Michigan State University to compost all of the garbage from the City of East Lansing, Michigan. A mechanical 8 deck continuous flow digester 10 ft. in diam. and 30 ft. high was constructed for this purpose. An average of 3 or 4 tons of garbage/day (straight garbage, no refuse or trash) reached the compost plant where it was ground in a heavy grinder. The ground material was either fed into the mechanical composter or hauled to a field and dumped into windrow piles. When the composting plant was in good operating condition about ⅔ of the garbage load could be effectively handled, with the remainder being hauled to the windrow field. Fig. 1 and 2 show a line drawing of the digester and two photographs of the compost operation.

During the 2 year period of plant operation numerous problems were encountered of both a mechanical and biological nature. In time, the plant was brought into a reasonable level of operation, although a large amount of physical labor was always necessary upon the part of the plant operators. At times the unit produced a good grade of compost upon a fairly routine basis. Plant upsets were always to be reckoned with and on occasion the operation gave off pungent and sometimes unpleasant odors. During most of its history, the plant could not be considered odor-free or unobjectionable to the community. These problems were made particularly difficult by the construction of university housing across the street from the compost plant.

The operation of a windrow type of composting also produced odors and a certain amount of nuisance. The windrow area was unfortunately located near another housing area and caused complaints whenever nuisances were produced. During the part of the compost operation in which raw garbage was ground and dumped upon the ground in windrows, little nuisance was produced. However, when these piles were broken into and repiled into windrows, by use of a soil shredder, odor nuisances were produced as might be expected.

It may be stated that most of the odor nuisance from the windrow operation was caused by attempts to compost material which had become putrid. Properly conducted windrow operations did not produce serious odors, but were not odor free because of the high temperatures of the compost piles and the attendant *steaming* during the turning operation. One unfortunate attempt to compost about 20 tons of ground garbage with daily turning by means of a front-end loader turned out particularly badly and had to be covered to prevent serious public health problems. Later operations with similar quantities of ground garbage in which a soil shredder was used for aeration were conducted without repetition of such incidents.

The Relationship of Composting to Air Pollution and Other Nuisance Probems

The above described experiences have shown that composting can be carried on effectively upon a municipal basis but that such an operation is not easy to conduct and that municipal composting must be considered as something of a question mark as a method of disposing of municipal wastes at this time. The economic value of composting as a means for disposing of solid organic wastes will be discussed later, and it will be shown at that point that the process does have certain definite advantages and is potentially a process of great worth.

However, in a consideration of the air pollution problems which may arise from large-scale composting it is necessary to be most realistic. The primary consideration that must be faced is that the material being dealt with is that part of the waste from a community which is most objectionable from an esthetic and public health standard. Garbage, at its best, is objectionable; at times, during hot summer months it may become downright putrid. Even trash, which is often mixed with garbage for composting, has definitely objectionable features. If sewage sludge is disposed of by composting, either separately or mixed with garbage or refuse, the potential for creating odor and other nuisances is high.

In this regard composting is not different from other processes for disposing of garbage, sludge and the like. Incinerators, sewage treatment plants and sanitary land fills are in a like position. All disposal methods for urban wastes must either be widely separated from the community which they serve or require expensive structures and equipment to prevent public nuisances.

As has been explained, effective composting commonly requires grinding. This operation, if in an enclosed building can be conducted with a minimum of nuisance, since ground garbage does not have a particularly offensive odor. However, the grinding of garbage in enclosed areas, unless fully automatic is most offensive to the workmen conducting the operation. Some ventilation is required; the more the ventilation, the greater possibility of creation of air pollution problems.

It has been the experience of this writer that garbage grinding in itself does not create serious odor problems, but could contribute to a general odor problem which might arise from a composting operation. Automatic grinders can be developed which may entirely prevent the development of odor nuisance during grinding.

After grinding, aerobic composting begins. By the very nature of composting the passage of air through or over the composting mass is essential. The air must be returned to the atmosphere, laden with moisture and whatever odors are produced in the composting process. During the early stages of composting a definite acrid or acid odor is noticeable, even though the material is in a aerobic state. Later, the odor becomes musty, and though not unpleasant to the casual visitor may become extremely objectionable to the inhabitants of the plant area

who must be faced with the plant odor upon a 24 hr. basis.

A city of 100,000 inhabitants produces 50 to 100,000 lb. of garbage/day. Using 50,000 lb. for a base of computations the moisture content will be about 30,000 lb., of which about 25,000 will be evaporated during the composting process if the end product material is dried to 20% moisture. In addition, moisture is produced during the aerobic degradation of the garbage, so that the total amount of moisture passing to the atmosphere would be 30 to 35,000 lb./day. As much as 50,000,000 ft.^{3} of air might be required to receive this quantity of water if it were to be disposed of by straight evaporation.

On cold days digesters usually *smoke*, that is, produce a typical steamlike water vapor. A similar type phenomena is noted with compost piles when turned during cold weather. Heavy moisture vapors are a serious consideration during periods of cold weather operation.

It would seem that large-scale composting operations will have to be conducted so that: (1) the operation is in a lightly inhabited area (or) (2) final drying is carried on in areas separated from plants built in inhabited areas (or) (3) high stacks are utilized for disposing of the moisture vapors (or) (4) the moisture vapors produced are recaptured.

Whether other odor problems will attend compost operations is not yet determined. These problems may not be serious if air supplies can be somewhat restricted without developing anaerobic conditions. If large quantities of air are required, composting may not be practical except in areas a mile or more from inhabited regions. This premise holds, regardless of the degree to which so-called *odorless* composting is developed, since the very nature of the process is such that a certain level of odors will probably be developed unless moisture and other vapors are recaptured.

Odor problems can probably be overcome, even in the more densely inhabited regions by use of tall stacks, high temperature burning of air and the like. However, these devices limit the economic value of composting and will probably have to be avoided if the process is to compete with incineration and other conventional methods. The most hopeful approach seems to be a recapture of water and odor vapors.

The above discussion presumes that large-scale projects of the scope discussed will be conducted under conditions similar to those now maintained in laboratories and in small scale operations. That is, it has been considered in these remarks that the composting will be properly directed and under the supervision of technical personnel qualified to conduct the operation in a highly competent manner. It has been amply demonstrated that improper and incompetent operation invariably results in foul odors which can cause complaints even at long distances from the plant or area of operation. No incompetent composting operation can be conducted for any great period of time in this country except in remote areas distant from human habitation.

The Future of Composting

Because this paper has been directed toward a discussion of some of the air pollution aspects of composting, there has perhaps been an unavoidable tendency to direct excessive attention to the problems which accompany these operations. In fairness to composting it should be called to the attention of the reader that many of these problems which have been discussed are common to all processes for the disposal of garbage, sewage sludge and refuse in urban areas. By their very nature these materials are objectionable, and at best their disposal results in some nuisance. Flies invariably follow garbage trucks and are concentrated at the point of disposal. Garbage trucks and the handling, grinding and burning or burying of such wastes all tend to make municipal disposal a difficult problem requiring judgment and experience.

It must be admitted that composting is unique among the methods now considered practical for solid organic waste disposal because the material must remain exposed to the air for long periods of time. Moreover, the processes result in large quantities of air being passed over or through the composting material. Therefore, by its nature, composting is a process which may discharge very measurable amounts of gas into the atmosphere which could cause unpleasantness and nuisance.

The possibility of recapturing much of moisture seems excellent, since only cooling of the discharged air is required. Moreover, studies now in progress indicate that composting can be carried on effectively with smaller quantities of air than have previously been presumed. If the quantity of air required for the process can be reduced without producing an odor nuisance, the overall problem will have been greatly reduced. It is such unknown factors which must be clarified before commercial composting can gain complete respect and confidence of engineers and public health authorities.

If properly handled, composting can probably be carried on at a lower cost than other disposal processes for this kind of waste. Neither heat nor fuel is required, and indications are that a large amount of material can be handled and composted on a relatively small area. Compost is a much more pleasant end-product than sewage sludge or other organics now commonly sold on the fertilizer market and can be produced with a nitrogen content of 5% or higher if desired. Nitrogen level largely determines the value of fertilizer, and compost must compete upon this basis, for the present at least.

The possibility of producing a material which will have economic value enhances the potential of the composting process and places it in a really competitive position with other waste disposal methods. In spite of wild claims for compost as an organic fertilizer by compost promoters and organic enthusiasts, the absolute value of compost for these purposes has not been definitely established. There is evidence that this material does have value and that it can be sold on a competitive market.

Conclusion

This article has been written to indicate the present status of composting, to discuss the principles involved in a very brief manner, to point out the air pollution aspects and problems which may arise and to mention the real potential which can in all honesty be assigned to the process.

In view of the course of development which composting is now taking, certain very definite air pollution problems will undoubtedly be encountered. The most serious of these problems stem from over-enthusiasm upon the part of promoters and others who do not completely understand the process. It must also be considered that even well engineered and properly managed plants built by men who understand the scientific principles involved will face certain air pollution problems. With effort these problems can probably be overcome, but this will not be easy.

Composting, as a process is now ready for fairly large-sized operations in areas where public nuisance will not be a serious problem. The process has not yet been developed to a state where it should be considered in urban areas. There are indications that composting may be feasible, even in heavily inhabited areas, but there is not yet enough experience to warrant such an undertaking, and it seems probable that such a plant would end in economic disaster.

Composting, as an economic, attractive

and useful method for disposing of organic wastes, may have much to offer. It seems probable that the use of this method of waste disposal will increase. The composting process is, therefore, a matter of real interest to air pollution engineers who are in a position to do much to increase its usefulness by their very special training and knowledge.

Report on Garbage Composting

ENGINEERING SOCIETY OF DETROIT
in Cooperation with the Dept. of Public Works and the Water Board

A resolution from the Detroit Common Council adopted Dec. 1, 1953, requested the Civic Affairs Committee of The Engineering Society of Detroit, in cooperation with the Department of Public Works and the Water Board staff, to study new developments for converting garbage into fertilizer that have been discovered in American cities or foreign countries, including the possibility of utilizing lands at the Detroit House of Correction as a depository for a plant processing site.

A subcommittee on Garbage Composting was appointed by the Civic Affairs Committee of The Engineering Society of Detroit and the organization's meeting was held April 5, 1954.

Procedure

The Committee established the following methods of procedure:

(1) No original research would be attempted by the committee.

(2) Research which had been conducted by others would be studied and evaluated.

(3) A bibliography would be prepared of all material published on the subject of garbage composting, subsequent to 1935.

(4) The Junior Section of E. S. D. would be requested to abstract all the articles selected from the bibliography according to the form prepared.

(5) The information prepared by the Junior Section would be reviewed and evaluated.

(6) A written report based on the evaluation would be prepared.

Scope of Research

A bibliography was assembled covering 620 references from which 158 were selected for study being those published since 1935.

In deciding to confine the research to material published since 1935, the committee was of the opinion that the earlier state of the art was so primitive that it would be of little value and certainly the proven earlier data would be included in the later works.

Recommendations

On the basis of the *evaluation of data* and *conclusions* which are appended hereto, the following are the findings of the committee:

(1) Garbage Composting either as a *waste disposal* or a *waste recovery* operation does not appear practical for adoption by the City of Detroit.

(2) The use of the lands of the Detroit House of Correction as a site for a *garbage composting* plant would be uneconomical.

Evaluation of Data

It was decided by the Civic Affairs Sub-Committee that the review of the literature should be abstracted so as to give information on 10 basic points:

A. Description of process and equipment.
B. Geographical location of unit.
C. Type of garbage used in process.
D. How collected.
E. Additives used.
F. Were buffers such as lime or shells used?
G. Composting time and temperature relationship.
H. Physical, chemical, and bacteriological composition of the end product.
J. Demand for and marketability of the end product.
K. Cost.

It was found that many articles and reports were sketchy and failed to give information on the above 10 points, sometimes covering only 2 or 3.

To summarize the information available to date, the following is submitted:

Description of Process and Equipment

The process may be *anerobic*, conducted in the absence of oxygen and requiring weeks or months for completion. It is considered this is unreasonably slow for a large community.

The process may also be *aerobic*, conducted in the presence of oxygen and requiring only a few days to produce a stable, inoffensive end product. This is the type of process which has received most attention in this country during recent years. In warm weather or southern climates the garbage is sometimes stacked in long rows 4 to 6 ft. high. These are turned over by hand or by power machines to permit air to reach all the contents of the pile. For colder climates, or to obtain better control, the garbage is sometimes placed in a bin or other container called a Digester. The air is supplied through perforations or other devices. Many of these have proved unsatisfactory due to poor aeration. A very advanced type of equipment is the experimental unit in use at Michigan State College. This is essentially a large cylindrical container with a series of shelves. The garbage enters at the top and is worked across the shelves by a stirring mechanism until it drops to the shelf below. This provides good turning to expose particles to the air and good circulation of air up through the drop holes. An installation of this type should be provided with auxiliary mechanical equipment: conveyors for sorting and transporting, efficient grinders, sprays for increasing moisture content, means for handling discharge or recirculating, *etc.*

Geographical Location of Unit

Composting in its more primitive forms is suited only to warm climates. However, the enclosed type of unit is suited to northern winters, relying for heat mainly on its own rapid oxidation. It is also more convenient to install in a

building than piles of garbage. The present control of the process gives no assurance it can be continuously operated without nuisance. Any installation would have to be remote from built-up areas. Scientific control is necessary, including trained personnel and laboratory facilities.

Type of Garbage Used in Process

Some reports are based entirely on a specific type of garbage such as *citrus waste*. However, much has been reported on usual commercial, domestic, or institutional garbage, evidently without newspaper wrapping. Moisture content should be adjusted to some amount between 40 and 70%. The optimum depends on the particular process.

How Collected

Garbage collection, if mentioned, was usually by means of trucks making pick-ups from individual homes and other usual sources. Many communities have collection of combined trash and garbage. This requires a large program—trash and salvage separation at the composting plant.

Additives Used

Additives reported were in order of usage: inorganic substances, bacterial cultures, and sewage in various forms. Of less importance were organic compounds (including earth) and use of recirculation to promote seeding. No additives whatever were used in some 26% of the processes reported. The number of additives used in any one process varied from 0 to 7. The use of only one additive was the condition in 46% of the reports. The rate of application of additives was rarely stated. The indication is that sludge, manure, and earth vary up to 25% of the compost dry weight (?). Bacterial cultures are added at the rate of an ounce or so/ton of compost. Patents are applicable (if still valid) to approximately 5 processes.

Were Buffers Such As Lime or Shells Used?

There may be some overlap into the topic of *additives*, as mainly lime in various forms was considered as buffer material. Fifty eight per cent of the composting was done without buffers (or no mention of them). Composting with lime was frequent (33% of the reports). The application rates where stated varied from 1½% to 4% (of weight of garbage). *Phosphorus* was stated as necessary in 1 report and mentioned in only 1 other. *Absorbents* were used to retain or recirculate ammonia by conversion to ferrous ammonium sulphate. Ammonium sulphate (with lime) was used at 1.6% and 3% application rate in 2 cases. Gypsum (with lime) was used in 1 case. Much composting is done without a buffer; lime is the only buffer frequently used; phosphorus in some form and ammonium sulphate and gypsum have slight usage.

Composting Time and Temperature Relationship

For open-air composting in piles, the time required is stated as 12 to 20 days, depending on favorable moisture content and a suitable ratio of the carbon to nitrogen (C/N) content of the raw garbage. When an efficient *digester* is used, good results are claimed in 3 to 5 days.

An efficient *aerobic* process is characterized by prompt rise in temperature to approximately 50° C., and continuing in the range of 50 to 60° C., until the process nears completion. This temperature is considered inhibitive to pathogenic bacteria and to fly eggs.

Over-compaction or excessive moisture content will prevent penetration of air into the pile. The lack of oxygen will cause the malodorous initial stage of *anaerobic* digestion to set in — in other words, the process goes sour.

Physical, Chemical, and Bacteriological Composition of the End Product

The physical appearance of the product after grinding should be that of humus or naturally decomposed organic matter. It should be inoffensive and the odor, if noticeable, should be that of soil or moulded leaves.

The chemical composition as to fertilizer components should be predominantly a small amount of nitrogen (1.2 to 1.6%). Some (less than 1%) potash and phosphorus will be present. Enrichment is possible by addition of commercial chemicals. The humus-like material is a suitable fertilizer base and soil conditioner. It no doubt contains trace amounts of a large number of chemicals important to plant life and not contained in chemical fertilizer.

The only bacteria of public health significance are the pathogens or those causing disease in man. These, as well as internal parasites, are claimed to be eliminated by a well controlled *aerobic* process.

Demand for and Marketability of the End Product

Good demand and profitable sales were reported in only 4 plants out of 27 in the U. S., or about 15%. Limited or poor demand was stated for about the same number. The majority of reports (74%) made no mention of sales.

The development of a market should be one of the first steps in a composting venture. The sales may be either wholesale, for disposing of large quantities in bulk, or packaging for the retail trade. The latter would no doubt require added chemicals to produce an acceptable fertilizer. In either case storage facilities are required and market fluctuations can be expected. The price of the product when reported covered a wide range above and below $25.00/ton of finished product.

Cost

The cost of constructing and operating a composting plant would vary widely with the design and locality. Some of the 1932 costs in Florida were $1600.00 to $2800.00/1000 population. A 900 tons/day *verdier* process plant for Miami, Fla., was reported to cost $2,600,000.00. A 265-tons/day mixed garbage and trash plant for Oakland, Calif. cost $715,000.00 *capital investment* and produces 125 tons of compost/day and 80 tons of marketable scrap. The process is one of sorting and stacking.

A plant involving sorting, grinding, and rapid digestion would require a great outlay for mechanical equipment. There is not sufficient information on such plants to make definite estimates on capacities and loading rates.

Conclusions

(1) The earlier work in composting and particularly in the parts of the world outside United States, has been toward the end of *waste recovery*. This was due to the poor natural resources and intensive farming of old lands, a sluggish technological advance, and a depressed economic condition.

(2) The value of composting in the United States lies principally in the field of *waste disposal*. Soil conservation and rebuilding in this country, through the use of organic (compost) fertilizers, has not been able to compete with plentiful low cost inorganic fertilizers.

(3) Composting as a method of waste disposal, presents some encouraging aspects where land available for disposal of municipal refuse is becoming increasingly more difficult to obtain and costly to use because of the longer distances to haul.

(4) The composting process, as regards the bio-chemical reactions involved, has been fairly well explored in California and elsewhere and the continuing work in this field by such agencies as Michigan State College along with several private agencies has provided considerable basic knowledge so that it can be said that from this standpoint the process is not without some degree of proof.

(5) *Anaerobic* composting, while accepted elsewhere, has failed in this country due primarily to the odor nuisance, the time involved in producing a stable product and the space requirements.

(6) The *aerobic* process is characterized by a minimum odor nuisance and rapid decomposition when compared to the older *anaerobic* process. The *aerobic* process is also adoptable to mechanical handling operations and limited space. For these reasons the *aerobic* process holds the most promise as a solution to the *waste disposal* problem in this country.

(7) The *aerobic* process has not as yet been proven satisfactory and as of this date there are no installations using this process, in operation in this country, except on an experimental or pilot plant basis. The principal reasons for the failure of the *aerobic* process are (a) Failure to solve the mechanical handling problems; (b) Failure to produce a stable product in sufficiently short a time period; (c) Failure to meet the high capacity and limited space requirements.

(8) Due to the fact that plant size composting operations have failed for various reasons, no reliable cost data are available and there is some doubt as to the economy of the process for large scale operation.

(9) The *aerobic* process, from the practical standpoint, is still in the experimental stage and its adoption by the City of Detroit would not be justified at this time.

(10) The use of the lands of the Detroit House of Correction as a site for the disposal of municipal refuse by any method, involves the element of excessively long hauls.

The hope of the composting process, when and if it becomes practical, is that, by its nuisance-free and small space requirements, it can be located near the origin of the refuse, thereby eliminating the costly long hauls.

Subcommittee on Garbage Composting

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The Determination of the Fluoride Content of Natural Vegetation*

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Fluoride contamination of vegetation is of increasing concern in agricultural and urban areas due to the growth and spread of certain industries. Although there is a limited concern with the toxic effects of fluorides on vegetation, the prime consideration is the effect that fluorides might have upon livestock eating contaminated vegetation.

The first step toward solving any such problem is to determine how far from the suspected source or sources these fluorides are found in concentrations sufficient to cause injury to livestock. Therefore, there must be carried out a sampling and analytical program so designed that statistical evaluations of all steps of the work will establish confidence in the results. This paper describes the procedures generally employed in such sampling and analyses, with examples of the evaluations used in the different steps.

Methods

Selection of Species

The vegetation species used in a study of this nature fall into 2 general categories. The first category is one or more species which can be found over a wide area; using this group, a measure of the geographical extent of an effluent can be made. The second category includes those specific feeds and forages which constitute the rations of the animals affected. Only the first will be discussed in this paper.

Different areas have different species which best serve this purpose. For a given area, the vegetation species, and in some cases the variety must be the same to get dependable results. Several factors enter into the selection of species: availability for sampling; general distribution over the area; mechanical ease of procuring material; and materials on which comparable age exposures are obtainable.

For example, in the Northwest, one of the most usable sampling plants for a wide area survey is the Himalayah blackberry. It is a cultivated plant but an escapee that now grows wild in every type of environment—around city dumps, vacant lots, in fir woods, fence rows, *etc.* The position of the large-sized leaves on the cane makes it possible to collect through the season leaves whose exposure times started closely together.

In the intermountain region in cultivated areas, alfalfa has been found to have remarkably uniform characteristics as to fluoride uptake. Different alfalfa varieties have been tested under field conditions, and there does not appear to be the wide variety of receptiveness to fluoride in alfalfa that is found in some other species.

It may be well at this point to caution against the use of Spanish Moss, although on the face of it this would seem to be an ideal material. It is universal, it is suspended in the air, and it derives all its

* Presented at the 49th Annual Meeting of the Air Pollution Control Association held at Buffalo, N. Y., May 20-24, 1956.

TABLE I.

Treatment	Location A		Location B		Location C	
	Avg. Conc.	Stand. Dev.	Avg. Conc.	Stand. Dev.	Avg. Conc.	Stand. Dev.
	ppm. F		ppm. F		ppm. F	
Unstored	87.0	2.3	37.3	2.2	11.4	1.1
Stored-limed	94.3	5.4	35.1	2.9	11.5	4.5
Stored-unlimed	87.6	8.4	37.4	4.3	10.1	4.7

nourishment from the atmosphere. However, it is extremely variable as far as its fluoride content in contaminated areas is concerned. Tufts of plant material growing side by side have been found to differ by several hundred percent in their fluoride contents.

Each geographical locality has one or more species that can be used as a measuring stick—weed, tree, or cultivated plant. Having decided upon a suitable species, the next step is to establish permanent sampling sites.

Selection of Sampling Sites

We have found that the best approach to a field sampling program is to make exploratory sampling on a transect basis, spokewise from the suspected source. The transects are selected to meet the topography and prevailing wind directions; exploratory transects in prevailing wind directions will be much longer than those vertical to the main wind axes.

From the results of the preliminary studies on the transects, the area to be covered by the permanent sampling sites can be outlined on a map. From the nature of the land use, the occurrence of natural obstacles, wind patterns, and species to be sampled, a decision can be made as to the arrangement of the sites. If the suspected source of pollution is located within fairly level land whose use is fairly uniform, a grid pattern of sites usually provides the most satisfactory information. If the land is broken, or if its use is diversified, then the location of sites along transect lines is usually the best arrangement.

Very often a combination of these 2 patterns is desirable. For example, in one area, land on one side of a fluoride source was irrigated level farm land in which field and other crops were grown, while on the other side the land was hilly and used mostly for pasture. The sampling sites were arranged in a grid pattern over the agricultural land and along transects through the pastured land.

After the nature of the pattern and the area over which the sampling is to take place have been established, the distance separating the sampling points has to be determined. With fluorides there is little advantage in having them closer together than ½ mile. If there is a predominant wind pattern so that the area fumigated is a long, narrow swath, it may be desirable to have the points ½ mile apart across the swath and 1 mile apart lengthwise of the area.

When the arrangement of the sites, the area over which they are to be located, and their distance apart have been decided, the sampling sites should be located on a map. Each theoretical site should then be visited to determine whether it is possible to obtain sufficient quantities of the species to be sampled. Of course the species need not be exactly on the designated spot, but if it is within half the distance to the next sample site it is satisfactory. If sufficient material for sampling is not found less than half the distance to the next sampling points, this point may be omitted from the sampling program.

Sampling

Portion of the Plant to Harvest

In all species we have worked with, the leaves and the chlorophyll-bearing portion of the stems have shown themselves to be the most vigorous absorbers of fluoride. Therefore, these tissues, particularly the leaves, are usually used in vegetation sampling to indicate the spread of fluorides in the atmosphere. Repeated tests of alfalfa have shown that the top 6 or 7 in. of the plant have the same fluoride content as the entire plant. With other species, especially the grasses, this may or may not be true, and the portion to harvest to provide the most reliable data must be determined for each species. With forage grasses, the most satisfactory technique is to harvest the regrowth that occurs following clipping or grazing. At each sampling date a large area may be clipped back to a standard height, say, 1 or 2 in., at each sampling site; hence, at the next harvest date abundant regrowth of the same age will be available at each site.

If trees are sampled, care must be taken to include leaves of the same age and from identical levels of the trees at each sampling. We have noted with heavy canopied trees that the tree screens itself (if it is a receptive variety like boxelder or cottonwood) and all samples should be taken on the side oriented toward the source of fluoride. Samples taken from all perennials should, as far as possible, be of the same age increment.

Amount of Material To Be Collected

In collecting the original sample, about 10 times as much material as is required for the final chemical analysis should be gathered. With alfalfa, about 20 gm. of fresh material are required for an analysis, so about 200 gm. should be gathered. With plants higher in water content, such as lettuce and spinach, more material is needed; with plants lower in moisture content, such as pine needles, less material is required. In all samples, care should be taken that parts of many plants are included. With alfalfa, the tops of at least 100 plants are harvested, the sampler usually cutting in a field in the form of a large *z*.

Sampling Errors Related to Variability of Material

In making routine samplings at specified sites, a single sample is usually taken from the field closest to the designated sampling point. The question immediately arises as to how near the value of the single sample is to the mean of the content of the field in question. To check on this point, it is necessary occasionally, to take several samples at random from a single field. This should be done at each harvest period and in fields of varying fluoride content. Results of many such tests with alfalfa, involving calculations of standard deviations, indicate that the results of a single sample 19 out of 20 times lie within 13% of the true mean of the field at that point, and 99 out of 100 times lie within 18% of the true mean. With pasture grasses, however, it is necessary to take 6 samples from a single field of the same size to obtain such accuracy. Pasture grasses usually vary a great deal more than alfalfa in their fluoride content.

Preparation of Samples for Analysis

Samples collected in the field are returned to the laboratory as soon as possible and are started in the analytical circuit. From each sample a portion of the vegetation is weighed out and placed in a heat-resistant metal container. The amount of material used for the sample depends upon the amount of moisture present and the expected fluoride content. Sample weights for analysis are quite variable, extending from 5 gm. for such dry materials as grain cereals to 100 gm. for types of vegetation high in moisture content, *e.g.* lettuce, fruits, *etc.* Two factors are important in the selection of a sample weight; there must be enough fluoride in the sample to give an adequate determination, and the amount of

ash produced upon calcining (usually not more than 5 gm.) must be of such a size as to allow an effective fusion with a reasonable amount of caustic. Many problems arise in the preparation of different types of vegetation. For example, grain cereals are very refractory to fusion with sodium hydroxide unless previously soaked for several hours in lime water.

Moisture Determination

Since the results of fluoride analyses of all types of vegetation are reported on a dry weight basis, it is necessary to determine the moisture content of the sample. This is done by weighing a small portion of the material, approximately 10 gm., into a previously weighed glass container. This container is then placed in a drying oven at 105°C. and dried to constant weight. Twenty-four hr. is usually sufficient time to dry the sample completely. The dried material is then removed from the oven, allowed to cool, and reweighed. The moisture percentage is calculated by using the difference in weights before and after drying.

Storage of Samples

Although every effort is made to prepare samples for immediate analysis, it is often necessary, because of the large numbers of samples arriving at the laboratory, to store them in some manner. An example using a commonly sampled material, alfalfa, will describe the storage procedure. In preparing alfalfa for deep-freeze storage, the procedure is to place 20 gm. of the material, detruncated into approximately ¾-in. lengths, into a plastic container (polyethylene or polystyrene). To the 20-gm. aliquot is added approximately 1 gm. of fluoride-free lime to fix any volatile fluorides that might be present. At the same time a second aliquot is weighed out, usually about 10 gm., to determine the percentage moisture of the sample. The moisture aliquot is dried to constant weight at 105°C. and the aliquot to be used for the subsequent analysis is placed in cold storage at 0°F. It should be pointed out that the moisture determination must be made when the sample arrives at the laboratory. The aliquot for analysis which is placed in cold storage can be so kept indefinitely.

Tests devised to show the effectiveness of storing alfalfa were carried out. At each of the 3 sites known to be of different fluoride contents, large quantities of alfalfa were collected. Twenty-four replicate samples from each of the 3 sites were prepared: 8 replicates were placed in the analytical circuit immediately; 8 replicates were weighed out and placed in suitable containers at 0°F. without lime; and 8 replicates were placed in storage with lime added (approximately 1 gm.). Moisture aliquots were taken immediately upon return to the laboratory. The samples were kept in storage at 0°F. for 4 wk. and then analyzed. The results of these tests are shown in Table I.

TABLE II

Results of Analyses of 50 Aliquots of a Single Sample by 5 Different Analysts

Analyst	Mean	Range	Standard Deviation of Single Determination	Fiducial Limits in %	
				P< .05	P<.01
A	17.0	16.8 - 17.3			
B	18.1	17.3 - 19.0			
C	18.3	16.8 - 19.9			
D	17.5	16.8 - 18.4			
E	17.8	17.3 - 19.5			
All	17.7	16.8 - 19.9	±.8	± 9.1%	± 12.6%

It is indicated that alfalfa samples can be stored in deep freeze prior to analysis. The preparation for cold storage should consist of weighing, liming, and the taking of a moisture aliquot. Although all stored samples exhibit more variation in fluoride content than those samples started in the analytical circuit soon after collection, the addition of lime to stored samples will reduce the sample variation. The errors due to increased variability can be minimized by carrying out replicate analyses on the samples. By standard statistical procedures it has been shown that 2 replicate analyses of the stored material will reduce the probable variations by 30%, while a sample value based upon 4 replicates will have only half the probable variation of a single analysis of the same material.

Chemical Analysis of Samples

Fluoride Determination

The Willard & Winter method for the analysis of fluoride in vegetation is in general the standard method used in the field of air pollution. A brief resume of the method is in order.

A weighed portion of the field sample is placed in a ceramic casserole or inconel dish of about 600-ml. capacity. The material is then covered with distilled water and 1 gm. of fluoride-free lime is added. The dish is placed upon a hot-plate and evaporated to dryness. It is then placed in a furnace and the material is ashed at 600°C. The ash is then fused with sodium hydroxide, the melt is dissolved in distilled water, and the resulting solution is transferred to a distilling flask. The fluoride, distilled as fluosilicic acid, is condensed in a water-cooled condenser and collected in a volumetric flask. A portion of the distillate is then titrated with standard thorium nitrate, using alizarin red as the indicator. The thorium reacts with the fluoride and removes it from the solution. The thorium then reacts with the alizarin indicator, forming a pink lake, the appearance of which indicates the end point.

Although the analytical method employed in the analysis of fluoride in vegetation is quite standard, there are certain precautions that must be observed. As in any quantitative analysis, blanks must be kept to a minimum. Equipment and reagent blanks must be frequently checked. It has been our experience that on occasion repetitive runs on the same equipment will give high and/or erratic blanks. For example, 5 consecutive runs using the same equipment throughout may give a blank of 20 μg. fluoride on the first run, 2 μg. on the second, 15 μg. on the third, 30 μg. on the fourth, and 52 μg. on the fifth run. This occurs in spite of extreme care in the cleaning of the equipment between the blank runs, and despite the stringent techniques used in the analytical procedure. These blanks do settle down after a number of runs, however. We feel that unless a constant check is made on all the equipment and all the reagents used, this is a very possible source of error in fluoride determinations.

Certain types of samples are more difficult to analyze than others. We have found, for example, that coal is one of the most difficult. Vegetation samples high in silica or samples high in alumina and silica are also difficult. The variations encountered in the latter cases are due to the difficulty in recovering the fluoride quantitatively. The problem involved in the high silica samples has been circumvented by utilizing the fusion method of Parks and Remert[1]. Fusion with caustic apparent-

[1] L. F. Remmert, T. D. Parks, A. M. Lawrence and E. H. McBurney. Determination of Fluorine in Plant Materials. *Anal. Chem.* 25, 450-53 (1953).

TABLE III

Analyst	% Difference between Expected and Observed Readings
A	−1.0
B	+4.0
C	−2.0
D	−1.5
E	+1.5
F	−1.5
G	−2.5
H	0.0
I	+1.0
J	+2.5
Mean	.05

ly converts the fluoride into a form which can be recovered in the distillation from perchloric acid at 135°C. Those samples high in alumina can be handled adequately if they are distilled from sulfuric acid at 145°C.

The volume of distillate that must be collected is dictated by the concentration of fluoride, silica, and/or alumina. The volume can be determined, if one has the experience, by observing the sample in all stages of its preparation.

It is highly desirable to have internal and external checks on the accuracy of the analyses. We have adopted the following procedure. Internal checks may be made by replicate analyses of the same sample by all operators in the laboratory. This includes all the variables introduced in the various steps. In addition, all operators titrate replicates of standard fluoride solutions to check the variation in this aspect of the procedure alone. External checks are made by exchanging samples with various other laboratories engaged in fluoride analysis. The statistical treatment of these data then gives an idea of what reliance may be placed upon the results produced by the analytical laboratory.

Calculation of Fluoride Concentration

Fluoride results are always reported as the concentration, usually parts per million (ppm.), on the dry weight basis of the plant material. The fluoride analysis gives the grams or milligrams of fluoride present in the analytical sample. The grams of dry material present may be calculated from the results of the moisture determination, since a standard amount of fresh material is used for the analytical sample. From these 2 values the ppm. of fluorides may be calculated.

Analytical Errors

In any chemical analysis there are certain errors inherent in the method; these must be determined. They arise from various sources, including differences among analysts and during various steps of the analysis. To obtain some idea of the errors involved in the analysis

TABLE IV

Sample	1	2	3	4
Expected Value	21.1	30.2	9.0	254
Lab V	24.0	36	8.0	212
W	21.0	31	8.0	245
X	24.0	33	9	245
Y	33.1	37	14.0	244

and among analysts, a large sample of alfalfa was dried and ground and thoroughly mixed. Fifty aliquots were then taken and distributed at random for analysis to 5 different analysts, 10 aliquots to each. The results of the individual analysts and the standard deviations calculated indicated that a single determination by an analyst picked at random would fall within 9% of the true mean 19 out of 20 times and within 13% of the true mean 99 out of 100 times.

Thus if a sample is brought into a laboratory, the results of the analysis will be in error by less than 9% about 19 out of 20 times, and by less than 12.6% 99 out of 100 times. Analytical errors are usually less than sampling errors. This means that to improve the value of the results obtained, more attention should be paid to sampling procedures than to analytical procedures.

One point often mentioned in fluoride analysis is the error involved in reading the titration end point by different analysts. Considerable effort has been spent in developing various spectrographic or colorimetric procedures designed to eliminate this source of error. To determine the significance of this error, 12 solutions containing known but varying amounts of sodium fluoride were prepared and aliquots of each were given to 10 different analysts. They were to carry out the titrations and record the resulting readings from the titration curve. These readings were then compared with the known readings. The amounts in the solutions varied from 0 to 45 μg. The readings for these values on the titration charts varied from 0 to 38. The greatest accuracy possible was 1 unit. The percentage differences between the expected and observed readings for each analyst are shown in Table III.

Calculations of standard deviations indicate that 99 times out of 100, titration end points and the resulting readings from charts will lie within 1.2% of the true value. This further suggests that such errors are exceedingly small and that improvement in techniques can be accomplished more easily in other phases of the process.

Standard Samples

As indicated above, the sampling and analysis of vegetation for fluorides are subject to many errors. An organization entering into such a program for the first time is desirous or should be desirous of having its results verified. A correct analysis involves proper sampling as well as good analytical techniques. One procedure followed has been for our own personnel to sample alongside the initiate's group in several fields at various distances from the fluoride source. Two aliquots of each sample are taken, one for each group to analyze. By comparing the results of the analyses, checks can be had on both the sampling and analytical procedures. Such a procedure has a certain drawback in that it often involves shipping samples for long distances, with accompanying delays, so that changes may occur during shipment which prevent the agreement of analytical results.

At present, another, more satisfactory, system is employed. The field sampling techniques are closely observed and suggestions for improvement or modification are made if necessary.

The actual chemical analysis is checked in the following manner. Stanford Research Institute has prepared large quantities of various materials, including soils, types of vegetation, ores, *etc.*, for analysis by drying and grinding. Twenty or more aliquots of these large samples have been analyzed for fluorides so that the fluoride contents of the samples are known, along with the variation that might be expected between analyses of aliquots from the same sample. If any laboratory wishes to have its fluoride analytical procedures checked, some of these samples are submitted to them for analysis under a number only. The label on the sample tells the type of material and gives a range within which the actual fluoride content falls. This range is given as an aid to the analyst so that he will have some idea as to the amount of material to use. Following the analysis, the results are submitted to us and we then report back the expected value. By receiving a few of these samples at regular intervals, a check is continually kept as to the reliability of the results of fluoride analysis. One laboratory receives 4 of these samples every month.

Some idea of the results we have obtained or the variability that exists among laboratories may be obtained from Table IV.

Of these analyses, the 2 underlined were beyond the expected range of variability. To date, about 100 of these sam-

ples have been submitted for analyses, and their use is increasing.

Results

Presentation

When the results of the analyses of the vegetation of all the sampling points sampled at any one time are available, they may be plotted on a map; then so-called *isofluors* are drawn. This is a line connecting points having the same fluoride concentration, *e.g.*, 30 ppm. The vegetation in the area between this line and the source will have a fluoride concentration of 30 ppm. or above. The remaining vegetation will have a concentration below 30 ppm. If forage plants are used, a 30-ppm. isofluor line is desirable, plus any other that may be of interest, such as 50 or 100 ppm. It is generally believed that 30 ppm. is about the maximum concentration of fluorides in forage that cattle with developing teeth can ingest without producing tooth markings. From such a map it is possible to ascertain at a glance how far from a source of fluoride the fluoride concentration has been raised above the safe feeding level. If the investigator is interested in the development of markings on vegetation, then the isofluor line should be drawn at the threshold concentration required to produce leaf markings on that particular species.

Following the procedures outlined above, the results obtained are fortified by:

1. Knowledge of variability of material
2. Knowledge of analytical errors
3. Knowledge of comparison of results by other laboratories.

In other words, complete knowledge of the reliability of the data is at hand. It is only by having such information available that claims can be approached with confidence.

Interpretation

The results of sampling and analytical programs must be interpreted with care. The results do show the limits to which the fluorides are distributed in concentrations sufficient to raise the level in the vegetation above normal. They also may be used to indicate the amount of reduction in output necessary to bring these limits up to a particular point, provided a sufficiently representative time period has been covered. The results cannot be used to indicate small changes in the amount of material put into the atmosphere by a given source. The plant is a living organism, not a dead absorber. During periods of rapid growth when material is being built up in the plant, the fluoride content on a ppm. basis will be much lower at a given atmospheric concentration than during a period when growth is slow. For example, around one source of fluoride the area enclosed by the 30-ppm. isofluor line at one season of the year is 4 times as large as at another season of the year even though there has been no change in the operation of the fluoride source.

When feeding of cattle is involved, the fluoride analysis of forage crops is of course of especial value in that it shows where stock may or may not be grazed with safety. The fluoride determinations are also of value in showing how effective the installation of fluoride emission controls have been, provided comparisons are made at the same season of the year and that the plants have been subjected to approximately the same growing conditions.

Automobile Paint Damaged by Airborne Iron Particles

E. G. FOCHTMAN and G. LANGER
Armour Research Foundation of the Illinois Institute of Technology
Chicago, Ill.

The management of a manufacturing concern found that a newly provided parking lot, the size of a city block, was little used despite the fact that the concern was located in a very densely populated industrial area. The people who had used the lot complained that the paint on their cars was severely damaged by some agent that caused the finish to be covered with small, strongly attached, brown particles. In some cases the cars had to be refinished after only a few weeks in the parking lot. Since the parking lot represented a considerable investment, a systematic study was undertaken to establish the cause of the paint damage.

The study was conducted in 3 steps:

1. Preliminary sampling and analysis
2. Controlled duplication of paint damage
3. Field sampling to locate the source

Preliminary Sampling and Analysis

Sampling was conducted in the parking lot area on 2 separate occasions. During one of these periods the wind direction shifted considerably and a number of samples were obtained. Several types of samplers were used since the nature of the pollutant was unknown. The fact that the paint was pitted seemed to indicate either a strong acid, a strong base, or an organic solvent. Examination of the damaged automobiles indicated the pollutant might be a red-brown particulate. In view of this the standard Smith-Greenburg impinger, with distilled water was used to trap any acid, base, or organic material. A cascade impactor sampler was used to obtain material for direct microscopic examination.

Samples of the material at the site of the paint damage were obtained by gentle scraping of the surface.

Laboratory examination of the Smith-Greenburg samples indicated the air did not contain either a strong acid or base. No odor of organic solvent was detectable.

Microscopic examination indicated magnetic particulates along with the usual background dust of an industrial area. This magnetic material was of rather odd shape and under low magnification it resembled the chip or shaving obtained when cutting metal with the lathe or by drilling. The material was in the form of spirals or ribbons. Particulate matter removed from the damage site was also magnetic. Photomicrographs of dust from various sources are shown in Fig. 1 - 3.

Thus the preliminary results indicated that there were iron particulates in the air and at the damage site.

A brief review of the literature did not reveal any reports of paint damage due to iron particulates and a limited laboratory study was undertaken.

Controlled Duplication of Paint Damage

Several automobiles in the parking lot were examined to determine the extent of the damage. In instances where the damage was slight, rubbing with mild abrasive renewed the surface while in other cases the damage had penetrated the paint for some distance. In severe cases the paint was completely ruined. A spot test for iron was conducted on several of the automobiles which did not have severe damage.[1] Iron was found at each damage site.

[1] The solution used was similar to the solution suggested by F. Feigl. Spot Tests—Inorganic Applications. Elsevier Publishing Co. (1954).

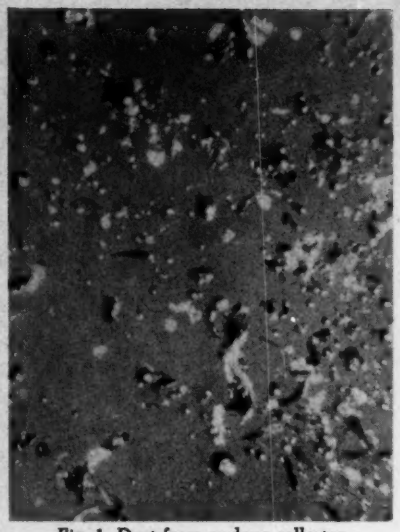

Fig. 1. Dust from cyclone collector.

Fig. 2. Dust from windshield of parked car.

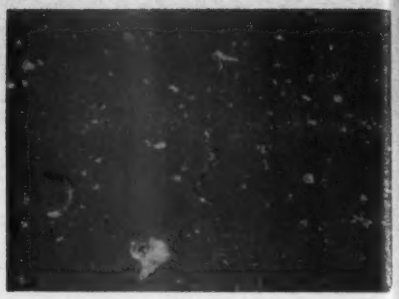

Fig. 3. Dust produced by grinding.

Test panels, both enamel and lacquer, used for the evaluation of automotive paints, were obtained from a paint manufacturer and placed in the parking lot. Other panels, obtained from wrecked cars, were also used. After an exposure of several weeks all panels were damaged and iron was associated with each damage site. (It is interesting to note that the paint manufacturers' test panels are made by painting an aluminum metal plate rather than a steel plate).

Exposure of these panels to iron particles in the laboratory indicated no damage after periods of up to several days. If iron was wetted with distilled water, damage was noted. Repeated wettings with tap water or exposure to rain caused more rapid damage. After the first few exposures to water the particles became firmly attached and continued to stain the paint. An automotive wax coating gave protection during the initial period of the test.

Field Sampling to Locate Source

The area within about 4 blocks of the parking lot was surveyed to determine possible sources of pollution. The preliminary sampling indicated that the source was probably west of the area and a sampler was devised to follow up this lead.

A sampler, complete with time device, was placed in the parking lot and operated from 8 a. m. to 4 p. m. The sampler was equipped with directional wind indicator and solenoid valves arranged in such a manner that the air was drawn through a parallel arrangement of a cyclone and a Smith-Greenburg impinger when the wind was from WSW to WNW and through another cyclone and Smith-Greenburg impinger when the wind was from any other direction. Results are given in Table I.

From these results it can be noted that the concentration of iron in the air when the wind was from the west is much higher than for any other direction. The high *background* concentration of iron was the result of dust caused by parking lot traffic; a random sample of the crushed rock of the lot indicated about 0.7% iron.

In order to locate the pollution source it was necessary to conduct sampling at various positions west of the parking lot. Consideration of the factors involved indicated that this could best be conducted using a portable sampler with a short sampling period. Analysis should preferably be conducted in the field to obtain as much information as possible with little waste effort.

The sample apparatus used for this is shown in Fig. 4. The sampler consisted of a filter holder, coarse paper filter, rotameter, control valve, 6 V air pump, and storage battery. Approximately 2.5 ft.^{3} of air was drawn through the filter in a 5-min. period.

Immediately after sampling the filter was removed, taking care not to dislodge any large particles on the surface, and placed horizontally in an open box. Three drops of a fresh solution of approximately 1/10% ammonium ferrocyanide in dilute hydrochloric acid were placed on the filter and it was permitted to develop for 5 min. in a closed box. The protection of the filter paper was found to be a necessary precaution since personnel, automobile finish and upholstery, as well as all other exposed surfaces became contaminated with iron particles during a short interval of exposure to the cloud.

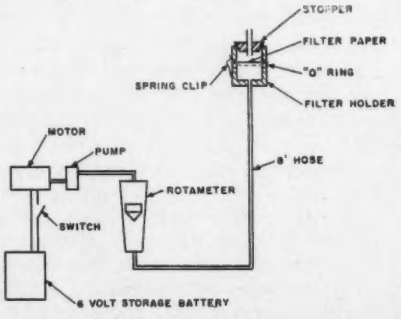

Fig. 4. Portable sampling apparatus.

After developing for 5 min., the number of blue spots caused by the iron particles were counted. A new sampling position was selected based upon results of the sample. In this manner it was possible to obtain 15-20 useful samples during a period of a few hours.

The results of this type of sampling are shown in Fig. 5. Sampling locations are indicated by the black circles, the lines point upwind and the number of iron particles/sample is indicated by the number at the end of the line.

Some samples, taken during lunch period, indicate a large reduction in particle count. The count increased immediately after lunch.

From Fig. 5 it can be seen that the source of pollution was close to the alley just north of Avenue C and just west of 2nd Street.

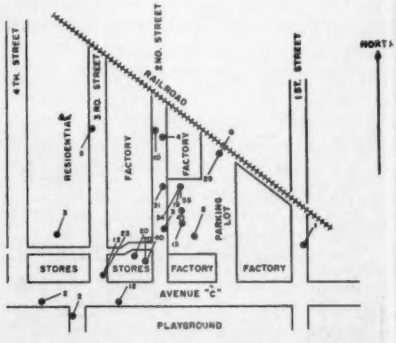

Fig. 5. Sketch of the survey area with particulate concentration and source direction indicated.

TABLE I

Analysis of Dust Collected by Directional Sampler

Test	Hrs. of Sampling of Wind from West	Hrs. of Sampling of Wind from all Other Directions	Mg. of Iron/1000 ft.³ Found When Wind From West		Mg. of Iron/1000 ft.³ Found When Wind from all other Directions		Ratio of Amount of Iron from West Compared to all other Directions	
			Cyclone[a]	Impinger[b]	Cyclone	Impinger	Cyclone	Impinger
1	13.8	16.0	0.35	0.33	0.30	0.24	1.16	1.36
2[c]	1.5	14.5	.48	1.78	.10	.23	4.8	7.68
3[c]	12.2	81.8	.52	0.97	.21	.21	2.5	4.5
4	7.3	10.5	0.51	0.92	0.37	0.60	1.4	1.5
		Average	0.46	1.00	0.24	0.32	1.9	3.1

[a] 8 cfm. [b] 1 cfm. [c] Lot was wet

Discussion

Many difficulties are associated with field sampling of air pollutants. The foremost difficulty is with the meteorological factors which must be considered. Sampling times and positions must be selected, based upon previous calculation or experience, such that it is possible to obtain significant samples. Although the behavior can be predicted approximately by the use of diffusion equations, the qualitative nature of the calculation and the time required to perform the calculation make it advisable to rely on the judgment of the testing personnel. This judgment often is based upon previous laboratory calculations, which indicate points likely to be of high or low concentration.

Another problem in the sampling from an unknown source is the variability of the dust emission. Thus, many processes emit dust only for a few seconds in several minutes, some for only a few minutes in a 24-hr. day, *etc.* In these cases, extensive sampling must be conducted to obtain significant results. This difficulty was not encountered here; in most cases the sample taken over a 5-min. period gave significant results.

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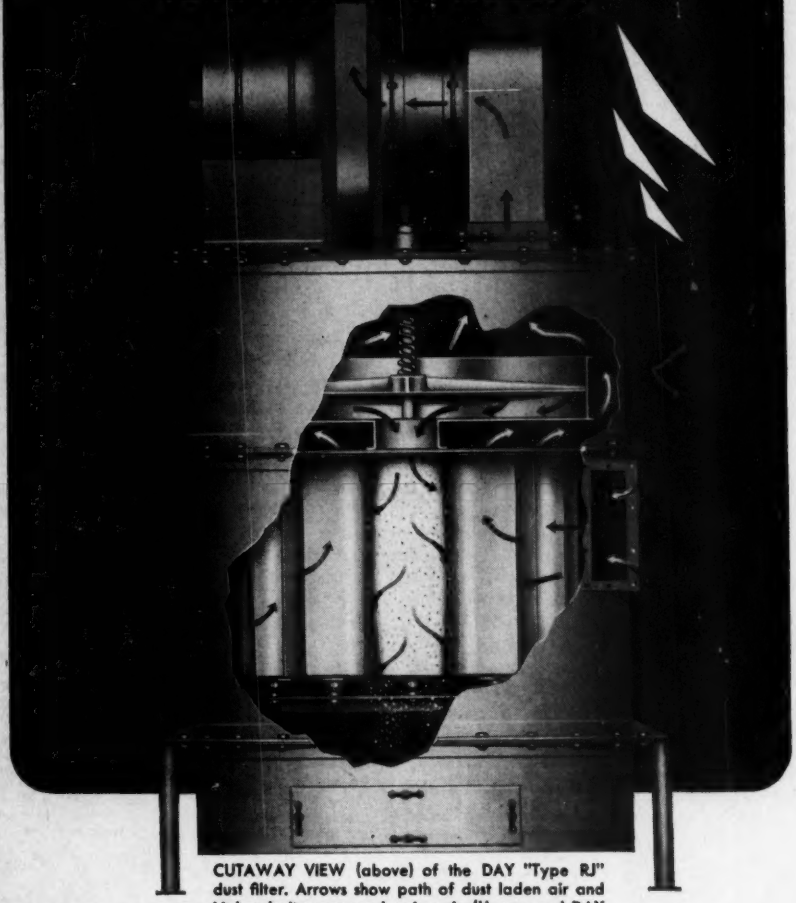

CUTAWAY VIEW (above) of the DAY "Type RJ" dust filter. Arrows show path of dust laden air and high velocity reverse cleaning air. (Hersey and DAY patents applied for.)

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The concentrations of the contaminant are usually very low and require extra care in sampling, handling, and analysis. In this case, the contamination of the area with iron or iron oxides presented somewhat of a problem during times when it was particularly dry and dusty or when the wind velocity was high and caused resuspension of dust on the ground, buildings, *etc.*

The large number of significant data obtained during this work was the result of finding the contaminant present in relatively high concentrations and of using a simple but effective field sampling technique.

Cause of Damage

Results of the examination of cars parked in the Company parking lot, exposure of painted test panels, and laboratory exposure of test panels indicate that the paint damage is caused by iron particles. The exact nature of the chemical reactions involved is more complicated than the reactions involved in the formation of rust; this reaction is still not completely understood.

Iron, exposed to the atmosphere, tends to form the metallic oxide. The oxidation is both a chemical and an electrolytic process; the presence of ions is indispensable to the reaction with oxygen.[2] It is generally considered that the reaction involves the formation of ferrous hydroxide, $Fe(OH)_2$, from the hydroxyl ions of water.

The sequence of events is believed to proceed somewhat as follows:

1. Large iron particles are deposited by gravity settling on the painted surfaces.

2. Water, from dew or rain and containing a dissociated chemical causes the iron to form ferrous hydroxide, a fairly strong basic material.[3]

[2] G. A. Greathouse and C. J. Wessel. Deterioration of Materials. Reinhold Publishing Co. p. 103 (1954).

[3] N. V. Sidgwick. The Chemical Elements and Their Compounds V II, p. 1328, Oxford at the Clarendon Press (1950).

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3. The ferrous hydroxide, in the form of a colloid, penetrates the paint surface.
4. The ferrous hydroxide is converted to a stable iron oxide.

Test panels were used to conduct controlled studies of the paint damage caused by iron particles made by filing a mild steel bar. It was found that dry particles caused no apparent damage over a period of several days. Tap water caused rapid staining of the paint and rusting of the particles. The pentration of the stain into the paint appeared to be a function of the time of exposure; wax such as Simoniz caused retardation of the staining and afforded some degree of protection.

Particles collected from the air at the parking lot were examined and found to be of curious shape. The shape was similar to metal chip formed by a drill. Other chips of a sliver shape were noted. It was found that these particles could be reproduced by grinding a high-speed carbon drill with a medium-coarse grinding wheel.

Location of Source

The method of source location used in this work has limitations imposed by particle size for effective analysis, background of pollutant, and a fairly serious drawback if the source is of intermittent nature.

It is interesting to note that the short distances of cloud travel and the high settling velocity of the particles cause the fallout pattern to be much shorter than the pattern calculated for gaseous diffusion. In this case local turbulence of buildings, trees, *etc.*, undoutedly have a pronounced, if not controlling, effect.

Multiple sampling made it possible to locate the source with a circle of about 15 ft. radius. Within this circle there were 2 exhaust vents. At least one of these vents was the exhaust from the ventilating system used to collect dust from the grinding of steel springs.

When the situation was called to the attention of the management, immediate action was taken to install more efficient dust collectors. As a result of this action there have been no more complaints of paint damage during the past year.

Acknowledgment

This work was conducted under the sponsorship of the Rock-Ola Manufacturing Company, Chicago, Ill., under the supervision of Morris A. Fisher, Supervisor, Fine Particles Research, Armour Research Foundation.

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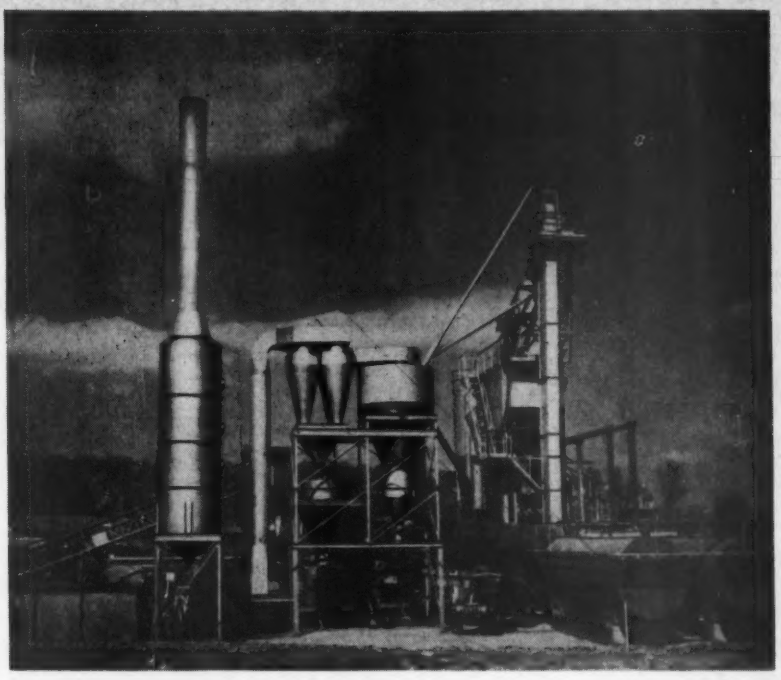

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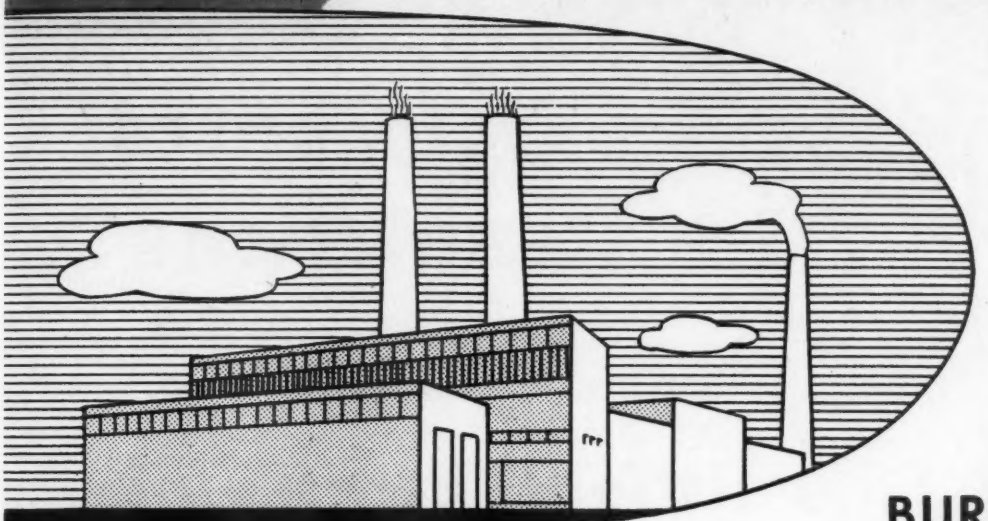

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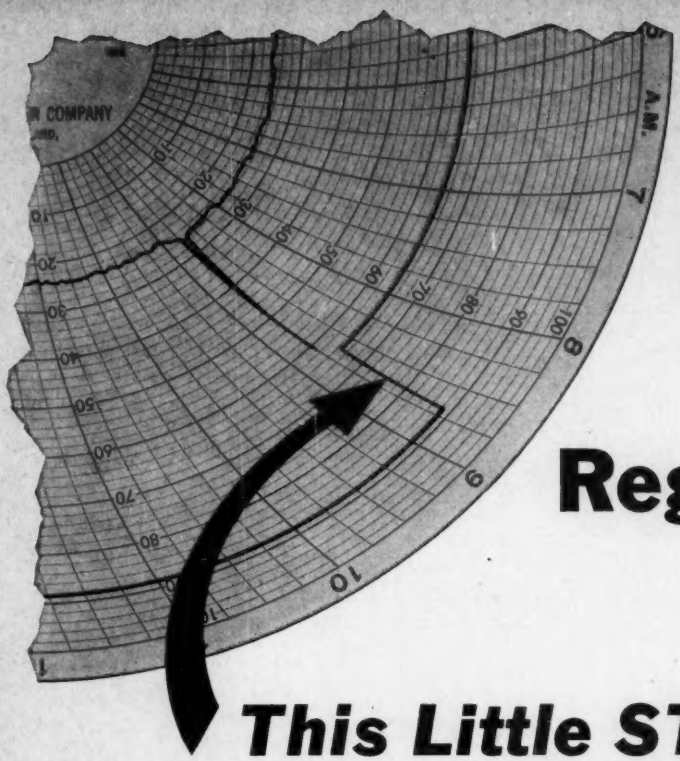

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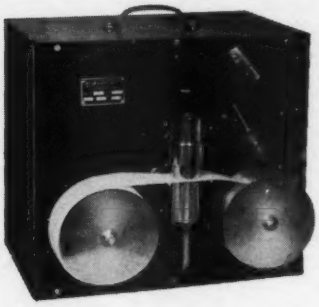

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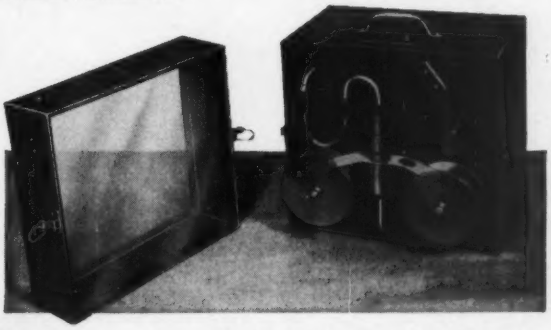

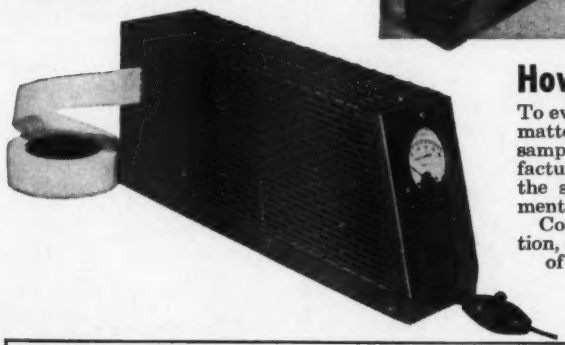

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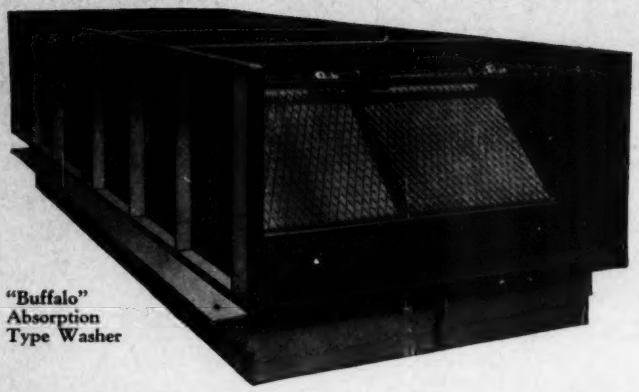

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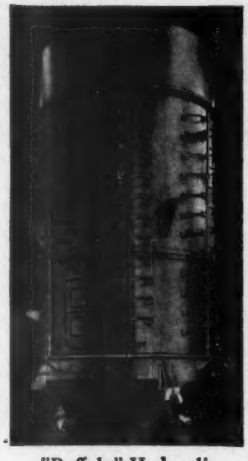
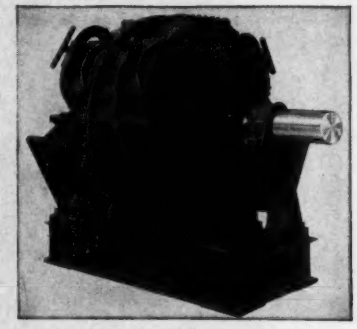


"Buffalo" Hydraulic Scrubbing Tower



"Buffalo" Rotary Gas Scrubber

"Buffalo" equipment includes Air Washers, Hydraulic Scrubbing Towers, Hydro-Volute Scrubbers, Rotary Multi-stage Gas Scrubbers, Gas Absorbers, Blowers, Exhausters and Pumps to solve most any cleaning problem you may have — all engineered to the job, for highest efficiency and simplest possible maintenance. Call on the "Buffalo" Air Engineer in any principal city for sound, helpful recommendations.

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How the Steel Industry Is Fighting Air Pollution

When the public hears about dust and fume control it is often in terms of what has not been done. It is important that they should also know what *has* been done, because the record of the steel industry is one of the most progressive.

The purpose of this discussion is to give the executives the facts to prove this point.

Q. *First of all, how can you measure the progress of dust and fume control in the iron and steel industry?*

A. As you know, there are many ways to combat air pollution. Equipment and methods vary in effectiveness, but the industry agrees that electrical precipitators have the highest collection efficiencies. By keeping track of the demand for this high efficiency equipment over the years, we can get a good indication of the importance the industry places on dust and fume control and the progress they are making.

Q. *Do these figures show an increasing interest in this high efficiency equipment?*

A. Suppose we let the figures speak for themselves. Since 1945 precipitator capacity in the steel industry had a greater increase than in any previous ten year period. Precipitators handling about 6½ million cfm were installed during this period.

Q. *But can't you attribute this growth to the increase in steel-making capacity?*

A. Some of this growth is due to expanded production facilities, but that's just a part of it. For instance, iron and steel production has increased about 30% since 1945 — but precipitator capacity has increased about 130% during this same period.

Q. *In the old days, I guess precipitators were used primarily in blast furnaces, weren't they?*

A. That's right. The first one went into operation in 1930. Since then, 169 Research Cottrells have been ordered by the industry.

Q. *What about new applications?*

A. We have a number of new uses that have proven themselves on the job. Open hearths, for instance. In one installation, our precipitators reduced stack discharge to a little over 2 pounds per hour. That's quite a reduction when you consider that the discharge without a precipitator ranged from 75 to 245 pounds per hour.

Q. *I understand your Cottrells are used on some sintering machines now. Is this true?*

A. Yes, we have three in operation and more under construction.

Q. *How about scarfing machines?*

A. This is a recent application which has worked out very satisfactorily. Two precipitators are now in operation on this application.

Q. *Has anything been done on such problems as iron cupolas, electric furnaces, and ferromanganese blast furnaces?*

A. Yes. Installations have been made on all these problems.

Q. *How do you go about developing these new applications?*

A. We work very closely with our customers on these new projects. Our laboratory is a big help, and our 40 years of pilot plant experience plus over 2,000 precipitators give us the kind of experience that leads to the successful engineering of projects like these.

If you would like to have more information about these applications, or if you want to investigate the possibility of using precipitators on other equipment, our nearest representative will be glad to call on you.

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